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GEOPHYSICS

A Journal of General and Applied Geophysics

Published by

The Society of Exploration Geophysicists

CONTENTS

45

Studies on Seismic Waves: I. Reflection and Refraction of Plane Waves *C. Y. Fu* 1

Studies on Seimic Waves: II. Rayleigh Waves in a Superficial Layer *C. Y. Fu* 10

Application of Continuous Profiling to Refraction Shooting *A. J. Barthelmes* 24

The Correlation Refraction Method of Seismic Surveying *J. A. Gillin and E. D. Alcock* 43

Refraction Exploration in West Texas *Sidon Harris and Gwendolyn Peabody* 52 45

Correlation of Refraction Shooting *G. A. Gamburtsev* 59
(Condensed by L. W. Gardner)

On Well Velocity Data and Their Application to Reflection Shooting *P. E. Narvarte* 66

Airplane Noise Interference with Seismic Prospecting *J. M. Kendall* 82

Depth-Displacement Slide Rule *W. R. Fillippone* 92

Patents 96

Discussions and Communications 103

Publications Received 104

Contributors 105

The Society Round Table

- Announcement of the Sixteenth Annual Meeting of the Society of Exploration Geophysicists 109
- Nominees for 1946-1947 Executive Committee 111
- Pacific Coast Meeting of the Society of Exploration Geophysicists 114
- Membership Applications Approved for Publication 116
- Statement of Ownership 118

Personal Items 119

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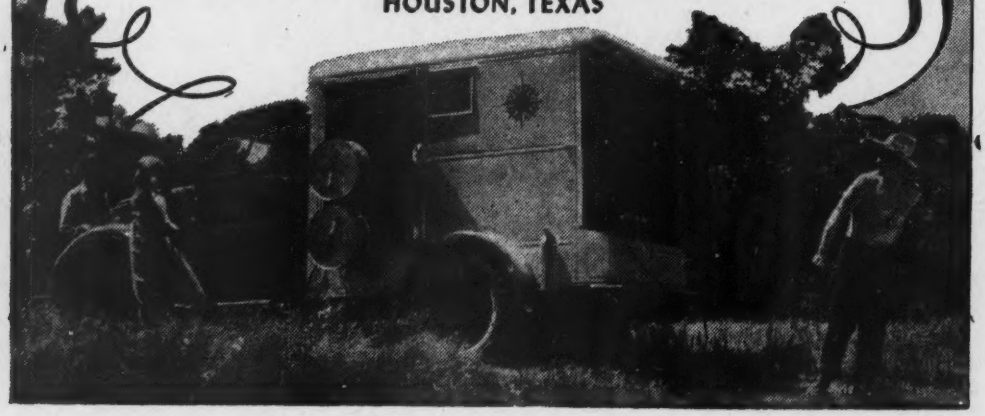

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Aims and Objects: The Society functions for the promotion of the science of geophysics, especially as it relates to petroleum geology and to the discovery and production of oil and natural gas and associated minerals, and the maintenance of a high professional standard among its members. Among the methods of accomplishing these objectives is the publication of papers, discussions, and communications of interest to the membership.

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These are only a few of the improvements. There are others too numerous to detail here. In fact, there is hardly a feature of construction which has not been improved. It will pay you to learn more about this outstanding instrument. Further details gladly furnished.

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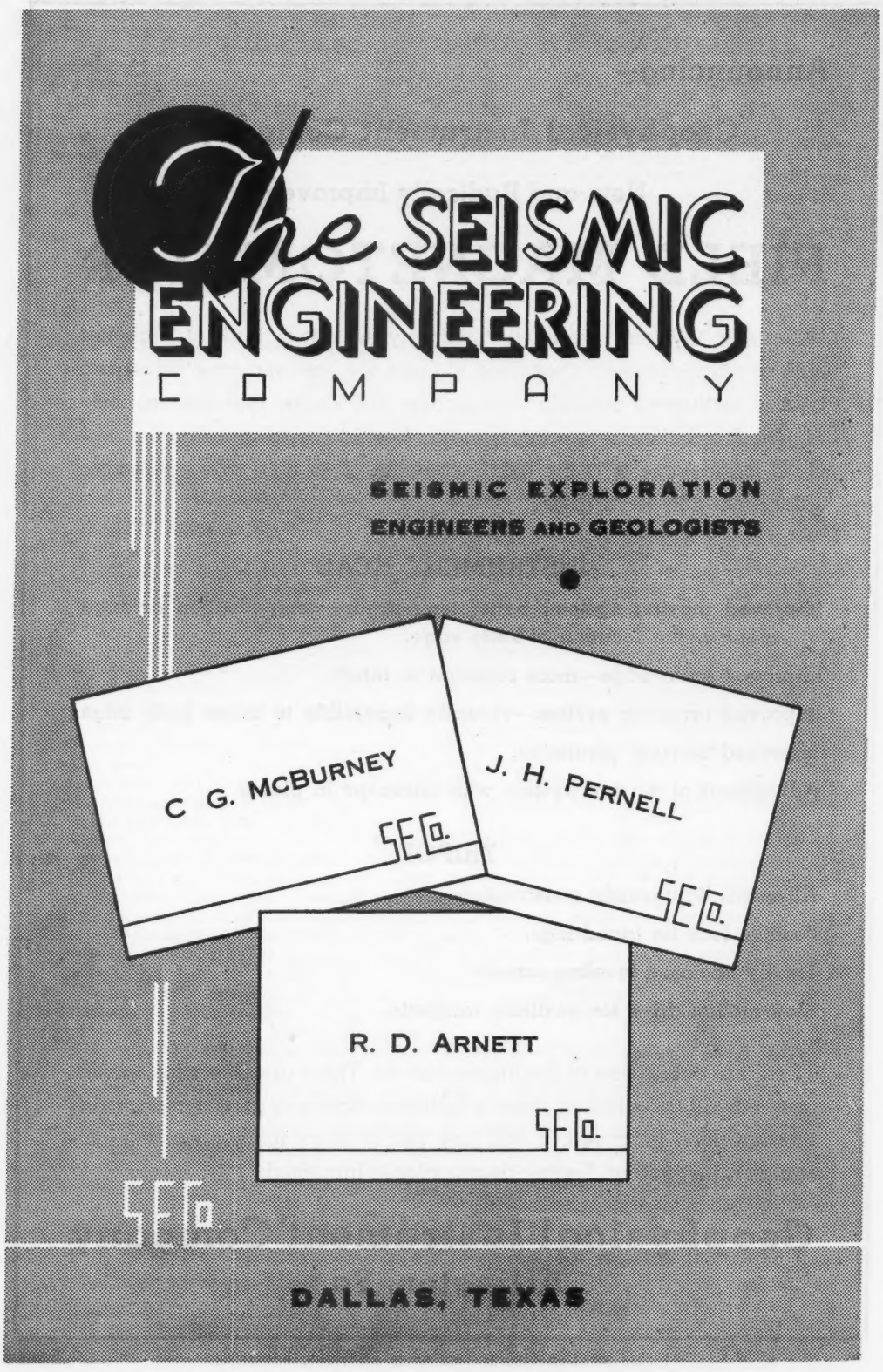
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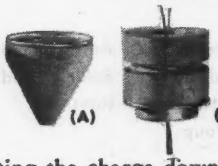

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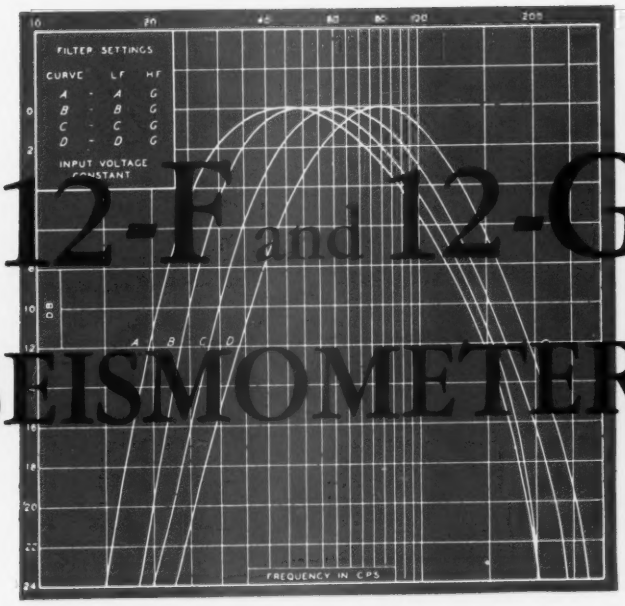


12-F and 12-G SEISMOMETERS

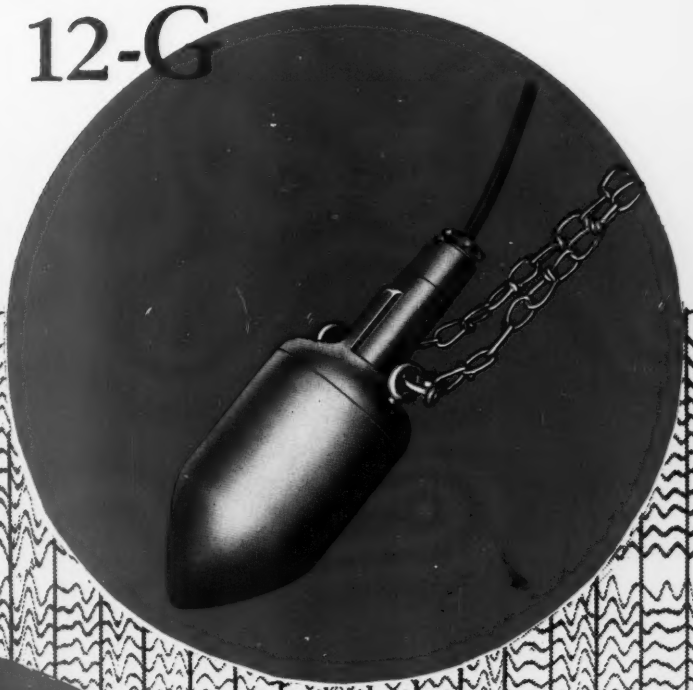
Folder No. 4

SEISMOMETERS

The National 12-F seismometer is an integral part of the National 25-A seismograph, and one, two, or three of these seismometers, depending upon the requirements of the survey, are used for each of the 24 amplifiers. This seismometer, which is of the dynamic type with the moving coil element used as the spring-supported mass, is electromagnetically damped and contains no fluids. It is of all-metal construction except for the electrical terminal mounting insulation and is hermetically sealed. The undamped natural frequency of the seismometer is approximately eight cycles per second. Its damping, which is entirely electrical, is sufficient to provide a velocity response which is essentially flat from 25 to 400 cycles. The National 12-F seismometer has been designed for use in surveys which are made on land.

The National 12-G seismometer is identical, except for the case, with the National 12-F seismometer. This seismometer has been especially designed for use in surveys where the instrument must be used beneath the water. The case is exceptionally strong and will withstand greater pressure without developing any leakage. The characteristics of the instrument are the same as those of the National 12-F seismometer.

12-G



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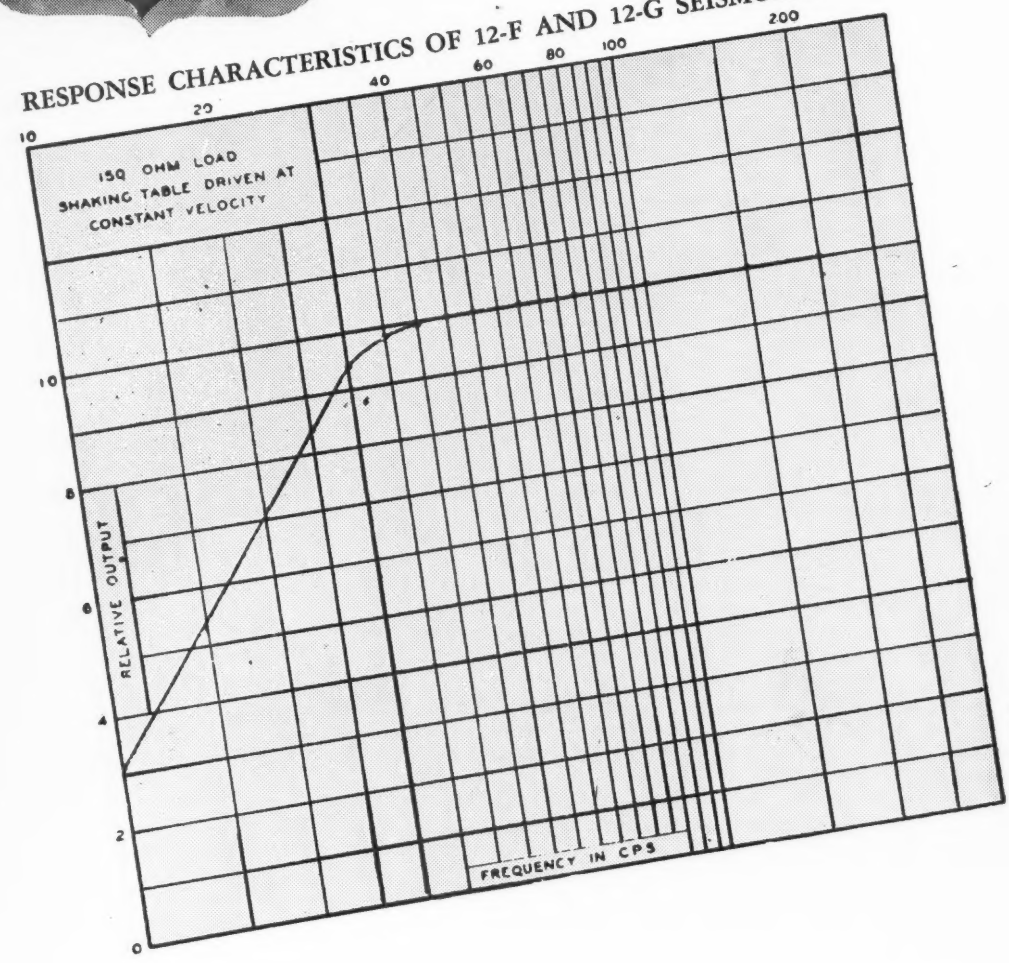
RESPONSE CHARACTERISTICS OF 12-F AND 12-G SEISMOMETERS



SPECIFICATIONS

12-F SEISMOMETER

Natural frequency—8 c.p.s.
Damping—electromagnetic
Response characteristic—
See above graph
Internal impedance—150 ohms
Sensitivity (150-ohm load) — 1×10^{-3} volts/mil/sec
Weight—5 pounds
Size—diameter 4", height 4"

12-G SEISMOMETER

This seismometer is the same as the type 12-F seismometer with the exception of the case. The 12-G seismometer has an especially designed, bullet-shaped case for use in swamp or water work.
Weight—7¼ pounds
Dimensions—
Height 11", diameter 3 15/16".

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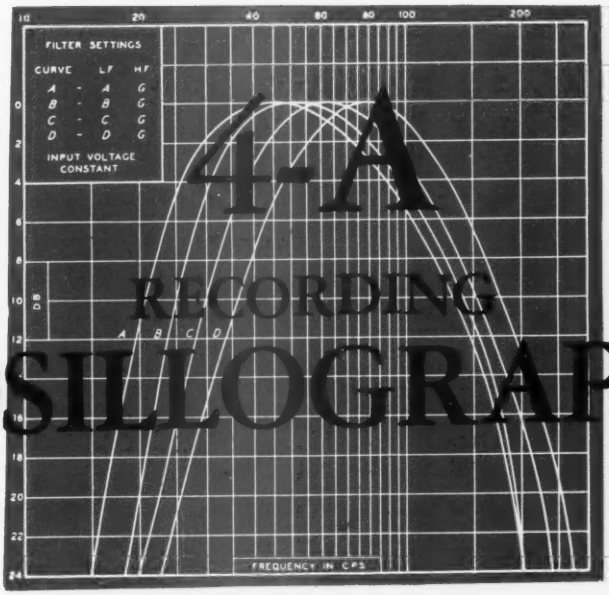

4-A RECORDING OSILLOGRAPH

Folder No. 5

National 4-A RECOSCIL

The recording oscillograph that is provided as standard equipment with the National 25-A seismograph comprises 24 mirror-type galvanometer units, highly sensitive, electromagnetically damped, and flat in frequency response over the seismic reflection range. The timing system incorporates a vacuum tube driven tuning fork, and a synchronous timing line motor. The recording paper is driven through the camera by means of a synchronous motor, insuring a constant paper speed. The camera is designed for use with recording paper of any width up to 10 inches.

SPECIFICATIONS

Recording elements—24
Damping—electromagnetic
Galvanometer size—diameter 1/4", length 3 1/2"
Galvanometer weight—0.33 ounces
Natural frequency—240 cycles
Paper drive—synchronous motor
Paper magazine—capacity, 200-foot roll of any width up to 10 inches
Timing—synchronous motor driven by tuning fork
Dimensions—13"x21 1/8"x8 3/4"
Weight—55 pounds

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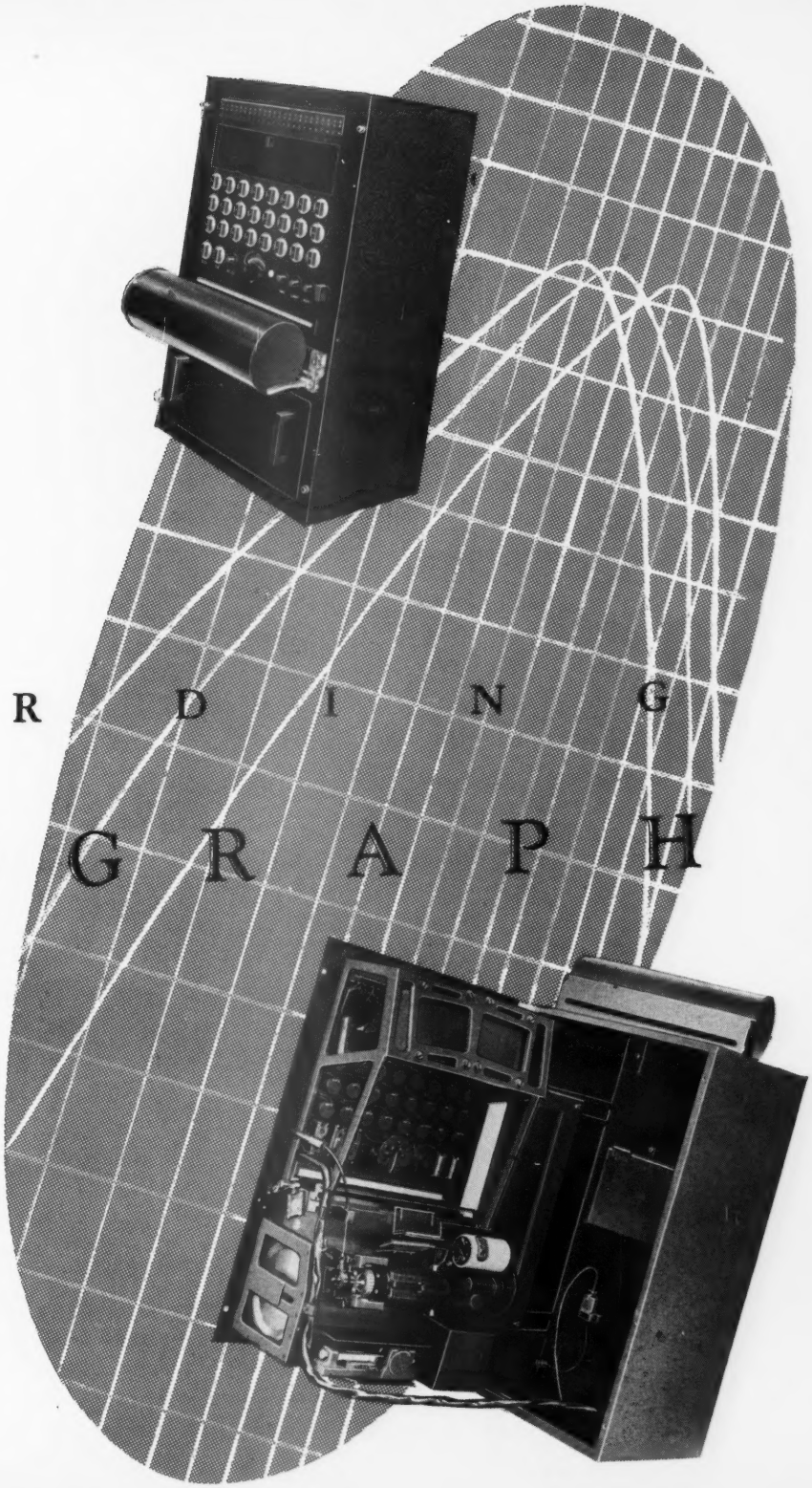

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TEST ROOM

The precision with which the National instruments are made requires the use of an electrically screened test room (shown above) for their final laboratory adjustment. Despite this precision in adjustment these instruments are extremely stable under field operating conditions and give little or no repair trouble.

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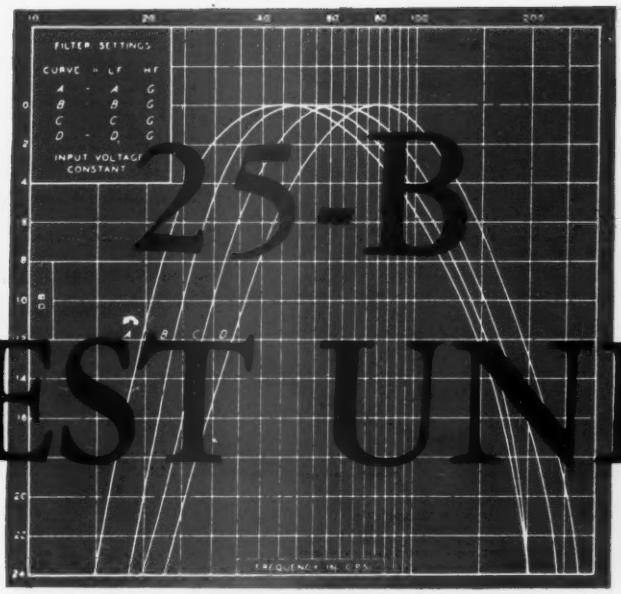

25-B TEST UNIT

Folder No. 6

National

25-B

TEST UNIT

This unit is a new addition to the Natio
equipment. All testing devices used in the
eration of the equipment have been locate
one panel for ease and convenience of test

This panel provides:

Equipment for testing the continuity
resistance of the cable and seismome
circuits.

Balancing circuits to minimize or elimin
interference from power lines.

A test signal generator for use in check
the performance of amplifiers, composit
panel and oscillograph under actual op
ating conditions.

Signal source for the operation of a porta
device used in the location of short circ
and open circuits in the seismometer cab

SPECIFICATIONS

Weight—27½ pounds

Dimensions—13½"x20¼"x11 15/16"

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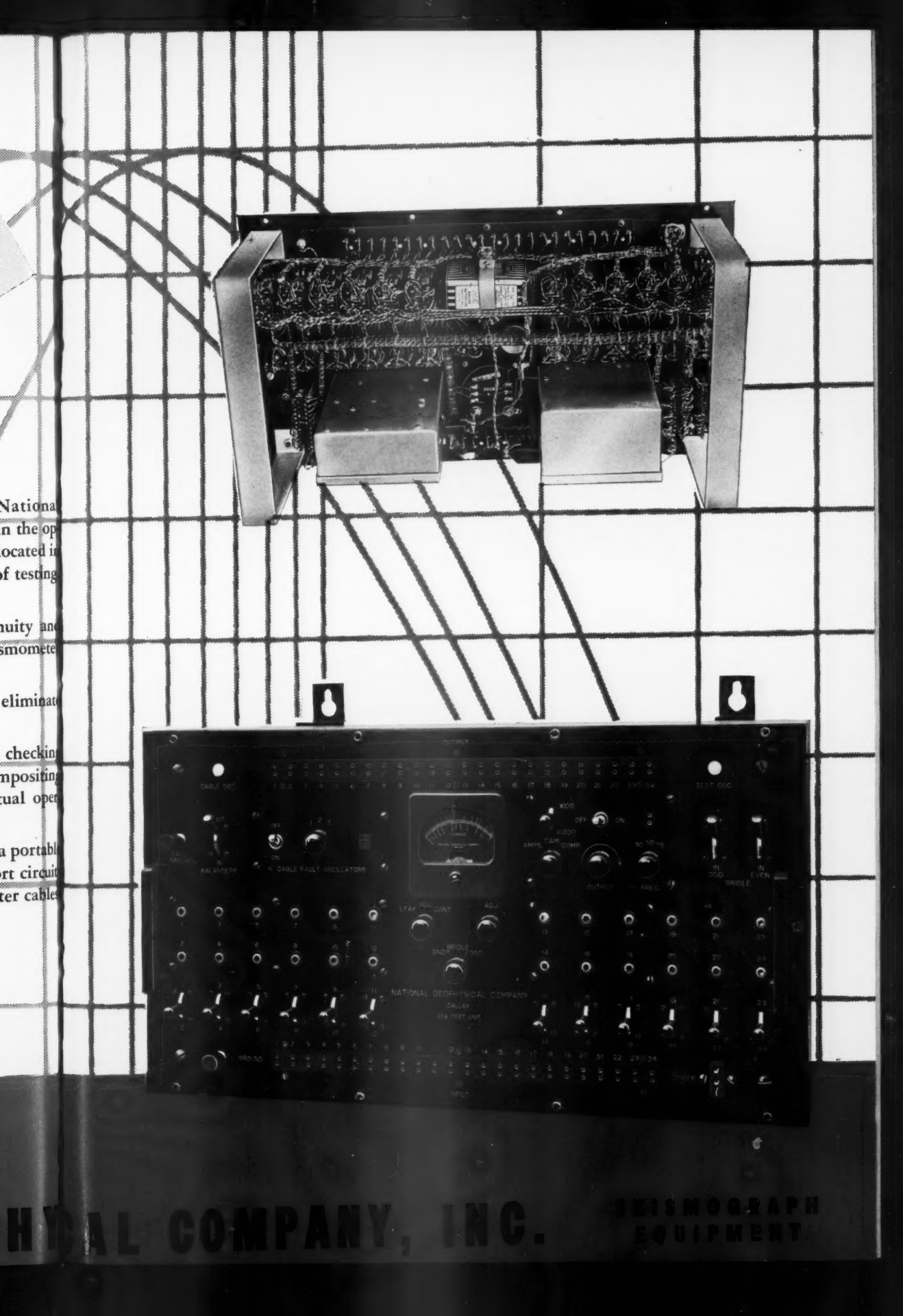

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SEISMOGRAPH
EQUIPMENT

Amplifier Maintenance Department

It has been the policy of National to make all repairs and adjustments to the amplifiers in the Amplifier Maintenance Department (shown above) of their laboratory. This policy requires amplifiers which are so designed that they give long trouble-free service under severe field conditions. The repair of the amplifiers in the central laboratory with experienced personnel and precision testing equipment insures the maintenance of their high quality of operation.

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Federal Electric Co., Inc. (Plastic Div.).. 7
C. H. Frost Gravimetric Surveys 34

General Geophysical Company 40
Geophysical Instrument Company 3
Geophysical Service, Inc. .....*Back cover*
Geotechnical Corporation 26
Gravity Meter Exploration Co. 15

Haloid Company 18
Harrison Equipment Company 38
Heiland Research Corporation 25
Hercules Powder Company 17

Independent Exploration Company .....
.....*Inside front cover*

Keystone Exploration Company 19

Lane-Wells Company 22

Magnetex 42
Mayes-Bevan Company 21

National Geophysical Company .....*Inserts*
L. S. Neuman 33
North American Geophysical Company .. 28

Petty Geophysical Engineering Company . 23

Robert H. Ray, Inc. 31
Rogers-Ray, Inc. 30
Ruska Instrument Corporation 29

Schlumberger Well Surveying Corporation 27
Seismic Engineering Co. ..... 4 & 5
Seismic Explorations, Inc. 16
Seismograph Service Corporation .....
.....*Inside back cover*
Southern Geophysical Co. 41
S. W. Ind. Electronic Co. 39
States Exploration Co. 45

Torsion Balance Exploration Company .. 15

United Geophysical Company 35
Universal Exploration Co. 26

Western Geophysical Company 24
Wolfson Instrument Corp. 6

PROFESSIONAL CARDS

Joseph L. Adler 11
Chester F. Barnes 14
Roland F. Beers 11
Thomas J. Bevan 13
John L. Bible 15
Hart Brown 13
R. H. Danna 15
J. H. Deming 13
H. M. Evjen 12
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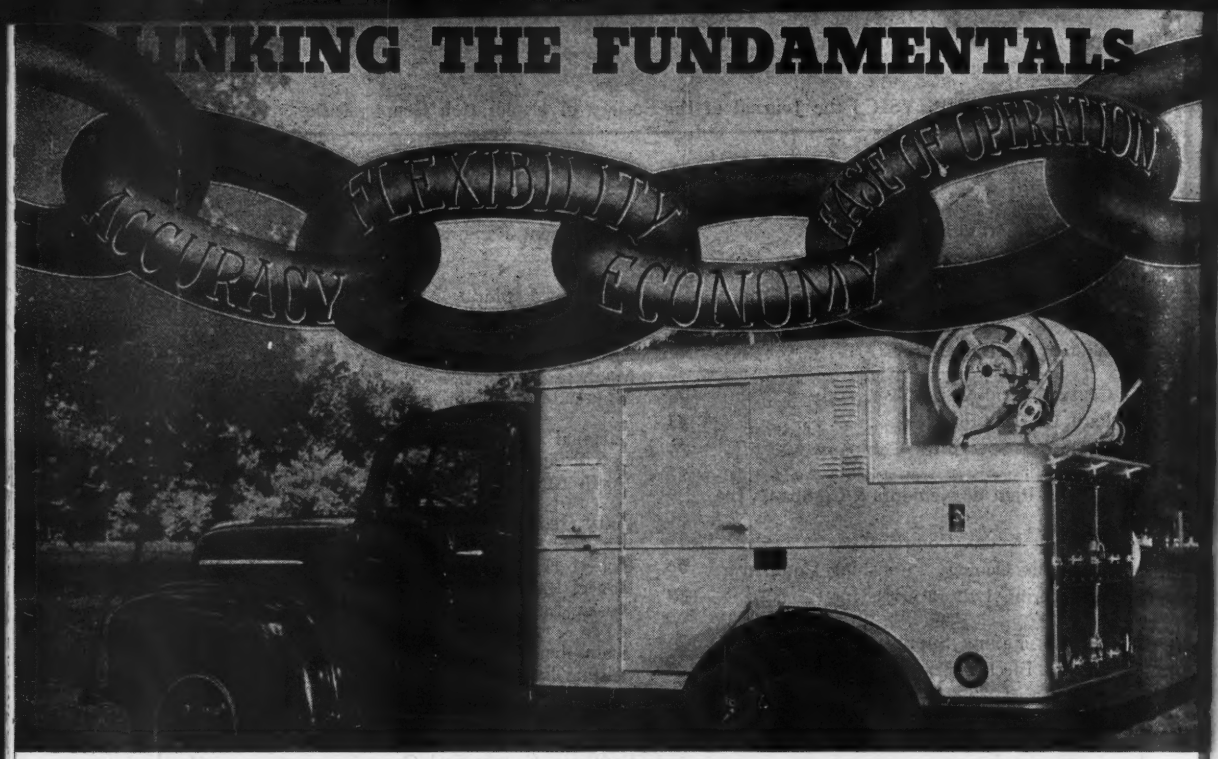
E. D. Williams 12
John H. Wilson 11
H. M. Zenor 14
Charles C. Zimmerman 13



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STUDIES ON SEISMIC WAVES: I. REFLECTION AND REFRACTION OF PLANE WAVES

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ABSTRACT

By taking the apparent velocity along the boundary as the parameter instead of the angle of incidence, the equations for the different wave amplitudes may be put in more symmetrical forms. In this way, it is more convenient to discuss both the body waves and the Rayleigh waves at the same time. A difficulty in the plotting of the square root of the wave intensity against the angles is also discussed. When the reflection or refraction coefficient is not real, the meaning of the intensity, as obtained by squaring the absolute value of the latter quantity, needs clarification.

1. *Introduction.* Even though the literature dealing with this problem is enormous, there seems to be still room for further discussions. The usual treatment of body waves and those of the Rayleigh type as two distinct entities sometimes puts an unnecessary limitation to the study of certain questions. For sinusoidal waves in the steady states, a time factor $e^{i\omega t}$ or $e^{-i\omega t}$ occurs in either type. If further, the media are homogeneous and the waves plane, both types exhibit periodicities along the boundaries. For Rayleigh waves, these space-periods give the true wave lengths; for body waves, only the apparent ones. The variations of the wave amplitudes in a direction normal to the boundary are different, but the difference lies merely in the transition from imaginary to the real domain of a single parameter. By taking out the periodic factors from the equations of motion, it is possible to discuss both types of waves from the same ordinary differential equations of a single variable.

Consider a plane wave of the form:

$$\phi = Ae^{i\omega[(lx+nz)/V-t]} \qquad (1)$$

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where A is an amplitude factor independent of x and z and l and n are the direction cosines of the wave normal. When this direction is real, the intensity of the wave is proportional to A^2. If this wave is incident on a plane boundary, the reflection and refraction coefficients of the amplitudes depend on l and n as well as on the material constants of the adjacent media. They are real when l and n are smaller than certain limiting values so that none of the angles concerned becomes complex.

The plotting of the different wave amplitudes against the angle of incidence is sometimes carried out indirectly by plotting the positive square roots of the intensities as calculated by squaring the corresponding coefficients. So long as the latter are real and there is no reversal of phase of the wave, this procedure is equivalent to the direct plotting of the amplitudes. But when there is a change of sign of the coefficient, the use of the positive square root of the intensity would amount to folding back a portion of the amplitude-curve. The result is the appearance of cusps on the curve, a peculiarity which is consequent upon the method of plotting rather than inherent to the theory. Besides, the reversal of phase would also thus be obscured.

When the reflection or refraction coefficient becomes complex, a common way to avoid the difficulty in plotting is to use its absolute value. Let this secondary wave be again of the form (1). Assume that the coefficient goes to the complex owing to l^2 being greater than 1. Then n becomes imaginary and (1) may be written as

$$\phi = Ae^{\pm\omega|n|z/V}e^{i\omega[(l/V)x-t]} \tag{2}$$

which is of the Rayleigh type, and its amplitude is generally defined by $Ae^{\pm\omega|n|z/V}$ which is a function of z. Although this is equal to A when $z=0$, the physical meaning of the complex coefficient becomes obscure when its absolute value is taken, because it is actually composed of two types of waves with amplitudes defined differently.

2. *Free Vibrations of Two Elastic Plates in Slipless Contact.* Instead of specifying the nature of the incident wave, we consider more generally the free vibrations of the system in Fig. 1. Two plates of thicknesses H_1 and H_2, densities ρ_1 and ρ_2 and Lamé constants λ_1, μ_1 and λ_2, μ_2 respectively are in contact. The planes $z=H_1$ and $z=H_2$ are free surfaces. The assumption of these surfaces is merely for the sake of taking account of the incoming waves on the plane of contact $z=0$.

The problem being two-dimensional with the motions independent of y, let us use the functions ϕ and ψ[1] defined by

[1] Lagrange's stream-function 1781; G. Green 1837; C. G. Knott 1899.

$$u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial z}$$
$$w = \frac{\partial \phi}{\partial z} - \frac{\partial \psi}{\partial x} \tag{3}$$

where u and w are the x- and z-components of the displacement respectively. For progressive waves sinusoidal in time, we may assume

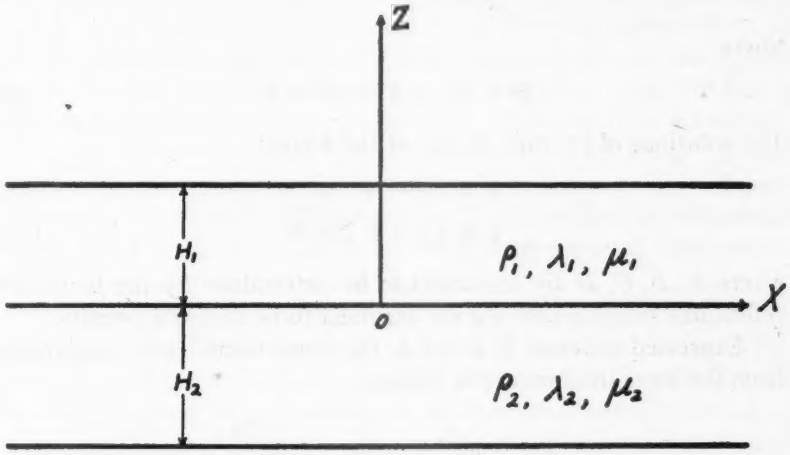

FIG. 1. Two elastic plates in contact.

a time factor $e^{-i\omega t}$ included in every solution. It will be omitted but understood in the sequel. In the steady state, ϕ and ψ satisfy the wave equations

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial z^2} + h^2 \phi = 0 \tag{4}$$

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial z^2} + k^2 \psi = 0 \tag{5}$$

respectively where

$$h^2 = \frac{\rho \omega^2}{\lambda + 2\mu} = \frac{\omega^2}{V^2}, \qquad k^2 = \frac{\rho \omega^2}{\mu} = \frac{\omega^2}{v^2} \tag{6}$$

and V and v are the phase velocities of the dilatational and distortional waves. Our purpose is to study the nature of the disturbances

which are periodic in x. By extending a method of Lamb[2] for a single plate, we want to seek solutions of the forms $\phi' e^{i\xi x}$ and $\psi' e^{i\xi x}$ where ξ clearly signifies 2π/wave length or ω/apparent velocity. Substituting in (4) and (5) and dropping the primes, we obtain

$$\frac{d^2\phi}{dz^2} + \alpha^2\phi = 0 \tag{7}$$

$$\frac{d^2\psi}{dz^2} + \beta^2\psi = 0 \tag{8}$$

where

$$h^2 - \alpha^2 = k^2 - \beta^2 = \xi^2. \tag{9}$$

The solutions of (7) and (8) are of the forms:

$$\phi = Ae^{i\alpha z} + Be^{-i\alpha z} \tag{10}$$

$$\psi = Ce^{i\beta z} + De^{-i\beta z} \tag{11}$$

where A, B, C, D are constants to be determined by the boundary conditions and $+\alpha$ and $+\beta$ are assumed to be real and positive.

Expressed in terms of ϕ and ψ, the stress components originating from the wave motions are as follows:

$$T_{zz} = \mu(\xi^2 - \beta^2)\phi - 2i\mu\xi\frac{\partial\psi}{\partial z},$$

$$T_{xz} = 2i\mu\xi\frac{\partial\phi}{\partial z} + \mu(\xi^2 - \beta^2)\psi. \tag{12}$$

The vanishing of stress at $z = H_1$ gives

$$\begin{aligned}(\xi^2-\beta_1^2)(A_1e^{i\alpha_1H_1}+B_1e^{-i\alpha_1H_1})+2\beta_1\xi(C_1e^{i\beta_1H_1}-D_1e^{-i\beta_1H_1})&=0\\ 2\alpha_1\xi(A_1e^{i\alpha_1H_1}-B_1e^{-i\alpha_1H_1})-(\xi^2-\beta_1^2)(C_1e^{i\beta_1H_1}+D_1e^{-i\beta_1H_1})&=0\end{aligned} \tag{13}$$

and that at $z = -H_2$ gives

$$\begin{aligned}(\xi^2-\beta_2^2)(A_2e^{-i\alpha_2H_2}+B_2e^{i\alpha_2H_2})+2\beta_2\xi(C_2e^{-i\beta_2H_2}-D_2e^{i\beta_2H_2})&=0\\ 2\alpha_2\xi(A_2e^{-i\alpha_2H_2}-B_2e^{i\alpha_2H_2})-(\xi^2-\beta_2^2)(C_2e^{-i\beta_2H_2}+D_2e^{i\beta_2H_2})&=0\end{aligned} \tag{14}$$

where the subscripts 1 and 2 refer to the upper and lower plate respectively. The continuities of stress and displacement at $z = 0$ result in the following four equations:

[2] H Lamb, *Roy. Soc. Proc. London A*, vol. 89, p. 114 (1917).

$$\begin{aligned}
&\mu_1(\xi_2 - \beta_1^2)(A_1 + B_1) + 2\mu_1\beta_1\xi(C_1 - D_1) \\
&\qquad = \mu_2(\xi^2 - \beta_2^2)(A_2 + B_2) + 2\mu_2\beta_2\xi(C_2 - D_2) \\
&2\mu_1\alpha_1\xi(A_1 - B_1) - \mu_1(\xi^2 - \beta_1^2)(C_1 + D_1) \\
&\qquad = 2\mu_2\alpha_2\xi(A_2 - B_2) - \mu_2(\xi^2 - \beta_2^2)(C_2 + D_2) \\
&\xi(A_1 + B_1) + \beta_1(C_1 - D_1) = \xi(A_2 + B_2) + \beta_2(C_2 - D_2) \\
&\alpha_1(A_1 - B_1) - \xi(C_1 + D_1) = \alpha_2(A_2 - B_2) - \xi(C_2 + D_2).
\end{aligned} \tag{15}$$

In (13), (14) and (15), we have eight homogeneous equations from which the eight constants can be eliminated. The resulting equation would be a relation between ξ, and h and k which depend on ω, or alternatively, a relation between V_a, the apparent velocity and λ_a, the apparent wave length. It is known as the frequency equation[3] and is a consequence of the boundary conditions. If this equation is satisfied, the ratios of the amplitude factors can be solved. By use of (3), the relative magnitudes of the displacement-components for the different waves may be calculated. However, it is not the problem in this general form that is of interest, but rather some of the special cases which may lend themselves to easy discussion.

3. *Reflection From a Free Surface.* We observe first the following: In (9) and (12), it has been assumed tacitly that ξ is the same for waves in both of the contacting media. This is justified by the boundary conditions which should hold at all times and for all values of x. When the factor $e^{i\xi x}$ is combined with the expressions (10) and (11) and if α and β are both real, it is seen that A and C are the amplitudes of the waves traveling towards the free surface and B and D, those of the waves traveling away from it. In the expression $e^{i(\xi x+\alpha z)}$, the direction ratios for the wave normal are given by $\xi : o : \alpha$. The direction cosines are therefore

$$\xi(\xi^2 + \alpha^2)^{-1/2}, \qquad o, \qquad \alpha(\xi^2 + \alpha^2)^{-1/2}.$$

For a dilatational wave incident at an angle i, we have

$$\sin i = \xi(\xi^2 + \alpha^2)^{-1/2}.$$

Similarly, if r and r_s are the angles of reflection for the dilatational and distortional waves respectively, we have

$$\sin r = \xi(\xi^2 + \alpha^2)^{-1/2}, \qquad \sin r_s = \xi(\xi^2 + \beta^2)^{-1/2}.$$

The cosines are expressed in the same way. Using (9) and taking ac-

[3] See, for instance, *Love's Theory of Elasticity*, 4th ed., pp. 178–179.

count of the way in which the reflection angles are reckoned, we have

$$i = r$$

$$\frac{\sin i}{\sin r_s} = \left(\frac{\xi^2 + \beta^2}{\xi^2 + \alpha^2}\right)^{1/2} = \frac{k}{h} = \frac{V}{v}.$$

Hence (9) expresses nothing else than Snell's Law.

Translating the origin to the plane $z = H_1$ and making both H_1 and H_2 very large, we have the case of a semi-infinite medium. The appropriate equations would be (13). When the incident wave is dilatational only, A, B, D exist, but $C = 0$. From (13), we have

$$\begin{aligned}(\xi^2 - \beta^2)(A + B) - 2\beta\xi D &= 0\\ 2\alpha\xi(A - B) - (\xi^2 - \beta^2)D &= 0\end{aligned} \tag{13a}$$

which yield readily

$$\begin{aligned}\frac{B}{A} &= -\frac{(\xi^2 - \beta^2)^2 - 4\alpha\beta\xi^2}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}\\ \frac{D}{A} &= \frac{4\alpha\xi(\xi^2 - \beta^2)}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}.\end{aligned} \tag{16}$$

It should be pointed out here that A, B, D are the amplitudes of the functions ϕ and ψ only. To get the amplitudes of the displacements, we have to use (3). Let $\mathcal{A}$, $\mathcal{B}$ and $\mathcal{D}$ be the amplitudes of the displacements corresponding to the incident, the reflected dilatational and the reflected distortional waves respectively. It can be shown easily that

$$\begin{aligned}\frac{\mathcal{B}}{\mathcal{A}} &= \frac{B}{A} = -\frac{(\xi^2 - \beta^2)^2 - 4\alpha\beta\xi^2}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}\\ \frac{\mathcal{D}}{\mathcal{A}} &= \frac{k}{h}\frac{D}{A} = \frac{V}{v}\frac{4\alpha\xi(\xi^2 - \beta^2)}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}.\end{aligned} \tag{17}$$

Substituting the angles

$$\sin i = \xi/h, \quad \cos i = \alpha/h, \quad \sin r_s = \xi/k, \quad \cos r_s = \beta/k \tag{18}$$

in these ratios, we obtain the familiar forms of the reflection coefficients for the displacements:

$$\begin{aligned}\frac{\mathcal{B}}{\mathcal{A}} &= \frac{v^2 \sin 2i \sin 2r_s - V^2 \cos^2 2r_s}{v^2 \sin 2i \sin 2r_s + V^2 \cos^2 2r_s}\\ \frac{\mathcal{D}}{\mathcal{A}} &= -\frac{2vV \sin 2i \cos 2r_s}{v^2 \sin 2i \sin 2r_s + V^2 \cos^2 2r_s}.\end{aligned} \tag{17a}$$

When the incident wave is distortional with the displacement lying in the plane of incidence, we have $A = 0$ and equations (13) are reduced to

$$\begin{aligned}(\xi^2 - \beta^2)B + 2\beta\xi(C - D) &= 0\\ 2\alpha\xi B + (\xi^2 - \beta^2)(C + D) &= 0.\end{aligned} \tag{13b}$$

Then

$$\begin{aligned}\frac{\mathcal{B}}{\mathcal{C}} &= \frac{h}{k}\frac{B}{C} = -\frac{h}{k}\frac{4\beta\xi(\xi^2 - \beta^2)}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}\\ &= \frac{2vV \sin 2r_s \cos 2r_s}{v^2 \sin 2r \sin 2r_s + V^2 \cos^2 2r_s}\\ \frac{\mathcal{D}}{\mathcal{C}} &= \frac{D}{C} = -\frac{(\xi^2 - \beta^2)^2 - 4\alpha\beta\xi^2}{(\xi^2 - \beta^2)^2 + 4\alpha\beta\xi^2}\\ &= \frac{v^2 \sin 2r \sin 2r_s - V^2 \cos^2 2r_s}{v^2 \sin 2r \sin 2r_s + V^2 \cos^2 2r_s}\end{aligned} \tag{19}$$

where it is understood that $r_s = i_s =$ angle of incidence.

It is seen that both the familiar cases are included in (13). Furthermore, in (10) and (11), it has been assumed that both α and β are real. If one of these becomes imaginary, the corresponding wave will change into one of the Rayleigh type. From (9), we have

$$\begin{aligned}\alpha &= (h^2 - \xi^2)^{1/2} = (2\pi/\lambda_a)\{(V_a/V)^2 - 1\}^{1/2}\\ \beta &= (k^2 - \xi^2)^{1/2} = (2\pi/\lambda_a)\{(V_a/v)^2 - 1\}^{1/2}.\end{aligned} \tag{9a}$$

Hence if the apparent velocity along the free boundary exceeds the body-wave-velocities, both α and β are real and we obtain the ordinary reflection coefficients when all the angles are real. If $V_a < v < V$, both α and β are imaginary and all the waves are of the Rayleigh type. As we remarked in the *Introduction*, the wave amplitudes would have to include the factors $e^{\pm\alpha z}$ and $e^{\pm\beta z}$. If we are concerned only with the plane $z = 0$, these would not affect the ratios in (17) and (19). The ratios $\mathcal{B}:\mathcal{A}$ and $\mathcal{D}:\mathcal{C}$ are real, but the ratios $\mathcal{D}:\mathcal{A}$ and $\mathcal{B}:\mathcal{C}$ are imaginary. Hence for waves of the same nature (both dilatational or both distortional), the phases are either the same or opposite to each other; for waves of different natures, the phases differ by 90°.

The situation is different when $v < V_a < V$, for then α is real, but β is imaginary. We have therefore a mixture of body waves and waves of the Rayleigh type. The ratios in (17) and (19) are all complex. In

view of the difference in the natures of the amplitudes for the two types of waves, the absolute values of these complex quantities do not seem to correspond to any physical reality. In a recent paper,[4] C. H. Dix gave a series of curves for $\mathcal{B}$ and $\mathcal{A}$ in (17) plotted separately against the square of the reciprocal of the apparent velocity. There, it was found that for a range of values of the latter quantity, $\mathcal{B}$ and $\mathcal{A}$ do not exist. The respective curves therefore show a peculiar series of points of discontinuities. From the above consideration, these simply mark off the range of V for which the two types of waves co-exist. From (9a), it is also seen that only dilatational Rayleigh waves can co-exist with distortional body waves but not the other way around.

4. *Reflection and Refraction at the Interface of Two Semi-Infinite Media.* If we push the planes $z=H_1$ and $z=-H_2$ both ways to infinity, we get two semi-infinite media in contact. The free surfaces serve no other purpose than providing sources for the incoming waves. The pertinent equations would be the set (15). If we disregard the interactions of the upper and lower boundaries as is necessary when we push them to infinity, we have only four equations in which there are eight arbitrary constants. The problem would be highly indeterminate if no further assumptions were made. In the problem of reflection and refraction, only the ratios of the different wave amplitudes are of interest. The equations (15) would permit only five of the constants to be arbitrary. Three conditions are therefore left at our disposal. By choosing them in different manners, we can cover practically all the cases that are treated ordinarily. We may assume the incident wave to come from above or from below; or we may assume it to be dilatational or distortional.

For an incident dilatational wave in the upper medium, we have the conditions: $D_1=0$, $A_2=0$, $C_2=0$. B_1 is the amplitude of the incident wave. Equations (15) then reduce to

$$\begin{aligned}
&\mu_1(\xi^2-\beta_1^2)A_1+2\mu_1\beta_1\xi C_1-\mu_2(\xi^2-\beta_2^2)B_2+2\mu_2\beta_2\xi D_2=-\mu_1(\xi^2-\beta_1^2)B_1\\
&2\mu_1\alpha_1\xi A_1-\mu_1(\xi^2-\beta_1^2)C_1+2\mu_2\alpha_2\xi B_2+\mu_2(\xi^2-\beta_2^2)D_2=2\mu_1\alpha_1\xi B_1\\
&\xi A_1+\beta_1 C_1-\xi B_2+\beta_2 D_2=-\xi B_1\\
&\alpha_1 A_1-\xi C_1+\alpha_2 B_2+\xi D_2=\alpha_1 B_1.
\end{aligned} \tag{15a}$$

As before, the equations (9)

$$h_1^2-\alpha_1^2=k_1^2-\beta_1^2=h_2^2-\alpha_2^2=k_2^2-\beta_2^2=\xi^2 \tag{9}$$

are equivalent to Snell's Law.

[4] C. H. Dix, *et al.*, *Quarterly of App. Math.* 3 (1945), 151–156.

When a distortional wave is incident in the upper medium, we have $B_1=0$, $C_2=0$, $A_2=0$ and D_1 is the incident amplitude. Equations (15) then reduce to

$$\begin{aligned}
&\mu_1(\xi^2-\beta_1^2)A_1+2\mu_1\beta_1\xi C_1-\mu_2(\xi^2-\beta_2^2)B_2+2\mu_2\beta_2\xi D_2=2\mu_1\beta_1\xi D_1\\
&2\mu_1\alpha_1 A_1-\mu_1(\xi^2-\beta_1^2)C_1+2\mu_2\beta_2\xi B_2+\mu_2(\xi^2-\beta_2^2)D_2=\mu_1(\xi^2-\beta_1^2)D_1\\
&\xi A_1+\beta_1 C_1-\xi B_2+\beta_2 D_2=\beta_1 D_1\\
&\alpha_1 A-\xi C_1+\alpha_2 B_2+\xi D_2=\xi D_1.
\end{aligned} \tag{15b}$$

For waves coming from below, the treatment is exactly similar. We may also make other assumptions, as for instance, a combination of different incoming waves, but we need not be concerned with them here. It can be shown that (15a) and (15b) are equivalent to the equations usually given for these cases.[5]

Since we have now four parameters α_1, β_1, α_2, β_2, there are additional possibilities for the combinations of the different types of waves. Conditioned by the relative magnitudes of the material constants of the media, some combinations may be forbidden. By use of equations similar to those in (9a) the discussion would follow the same line as before and no new light would be thrown there.

It is thus seen that there are inherent interrelations between body waves and Rayleigh waves, and among several of the cases generally treated separately. By the present method of approach, they may be discussed in a more concise manner. It should also be pointed out that the waves of the type SH are not contained in (3). They are comparatively simple although not included in the present scheme.

ACKNOWLEDGEMENTS

The studies are part of the program on theoretical research carried out in the United Geophysical Company in Pasadena, California. I wish to acknowledge my indebtedness to Dr. C. H. Dix and the management of the company for the permission to publish these results.

[5] See, for instance, Macelwane's *Theoretical Seismology*, pp. 159, 169; Muskat and Meres, GEOPHYSICS V (1940), 115.

STUDIES ON SEISMIC WAVES: II. RAYLEIGH WAVES IN A SUPERFICIAL LAYER*

C. Y. FU†

ABSTRACT

Lamb's method in the theory of the plate is extended to the case in which one of the surfaces is not free. The resulting determinantal relation is similar to that of Sezawa. It is then simplified and special cases of the frequency-velocity relation are discussed. Even when the thickness of the layer is as small as a wave length, the interaction of the upper and lower boundaries of the layer is quite slight and Rayleigh waves and Stoneley's waves may be discussed separately. A few points in connection with the application of this frequency relation to the ground roll problem are also discussed.

1. *Introduction.* In the theory of the simple Rayleigh waves, the medium is assumed to be homogeneous and semi-infinite in extent. The velocity of the surface waves so obtained depends on the material constants of the medium only and is *independent* of the frequency of the waves. On the other hand, if the medium is overlain by a layer of a different material, waves not only of the Rayleigh type but also of the Mock-Rayleigh type[1] will both exist in the layer. The disturbance resulting from the superposition of these two types of waves, when analyzed into harmonic components along the boundary, travels with velocities depending on the frequency. We have thus a dispersion of the Rayleigh waves, the latter being understood in the general sense. In seismic explorations, the existence of a superficial layer is by far more in accord with the experience and the circumstances for the generation of the simple Rayleigh waves are seldom realized. The dispersed waves make their appearance in groups whose velocities give the rates of the transmission of energy. Whether the wave groups recorded in the seismograms are entirely due to dispersion or not will not be discussed here, but the effect itself is inescapable if the theory of small displacements is maintained.

As an extension of Lord Rayleigh's original work on surface waves, the present problem was attempted a long time ago by Love[2] with the assumption of incompressibility. By the same method, the work was

* By permission of the United Geophysical Company, Pasadena, Calif.

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[1] H. Bateman, *Math. Rev.*, Vol. 5, p. 205 (1944).

[2] A. E. H. Love, *Some Problems of Geodynamics*, Cambridge, 1911.

followed up by Sezawa,[3] Stoneley,[4] Lee[5] and some others, the compressibilities of the media being taken into consideration. However, the problem may also be approached from a different direction. The propagation of waves in an elastic plate bounded by free surfaces has been studied by Lord Rayleigh[6] and also by Lamb.[7] The method used by the latter was refined in his later paper with even more clarity and elegance. We have applied the method to the discussion of reflection and refraction of plane waves, but if we regard one of the two surfaces of the plate as being *not free*, we can easily extend Lamb's method to the present problem. Although it is actually a special case of our previous study, we propose to discuss the problem anew in more detail.

2. *The Method of Normal Functions and the Frequency Equation.* Let the layer of thickness H elastic constants λ_1, μ_1 and density ρ_1 overlie a semi-infinite medium of constants λ_2, μ_2 and ρ_2. Let the co-

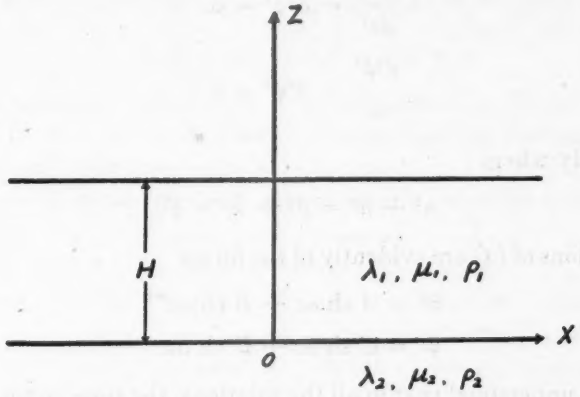

FIG. 1. Co-ordniate axes and notations.

ordinate axes be chosen as shown in Fig. 1. Expressing the displacement components u and v by

$$u = \frac{\partial \phi}{\partial x} + \frac{\partial \psi}{\partial y}$$
$$v = \frac{\partial \phi}{\partial y} - \frac{\partial \psi}{\partial x} \qquad (1)$$

[3] K. Sezawa, *Bull. Earthquake Res. Inst. Tokyo*, vol. 3, p. 1 (1927).

[4] R. Stoneley, *M. N. R. A. S. Geophys. Suppl.*, vol. 3, p. 222 (1934).

[5] A. W. Lee, *ibid.*, vol. 3, p. 83 (1932); vol. 3, p. 238 (1934).

[6] Lord Rayleigh, *Proc. Lond. Math. Soc.*, vol. 20, p. 225 (1889).

[7] H. Lamb, *Proc. Lond. Math. Soc.*, vol. 21, p. 85 (1889); *Proc. Roy. Soc. London A.*, vol. 93, p. 114 (1917).

we obtain the equations of motion in the steady state

$$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial z^2}+h^2\phi=0$$
$$\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial z^2}+k^2\psi=0 \tag{2}$$

where

$$h^2(\lambda+2\mu)=\mu k^2=\rho\omega^2 \tag{3}$$

and ω is the angular frequency of the wave. Solutions which are periodic in x may be written in the forms $\phi=\phi' e^{i\xi x}$ and $\psi=\psi' e^{i\xi x}$. Then ϕ' and ψ' satisfy

$$\frac{d^2\phi'}{dz^2}-\alpha^2\phi'=0$$
$$\frac{d^2\psi'}{dz^2}-\beta^2\psi'=0 \tag{4}*$$

respectively where

$$\alpha^2+h^2=\beta^2+k^2=\xi^2. \tag{5}$$

The solutions of (4) are evidently of the forms

$$\phi'=A\ \mathrm{sh}\ \alpha z+B\ \mathrm{ch}\ \alpha z**$$
$$\psi'=C\ \mathrm{sh}\ \beta z+D\ \mathrm{ch}\ \beta z. \tag{6}$$

It is to be understood that in all the solutions, the time factor $e^{-i\omega t}$ has been omitted, and $+\alpha$ and $+\beta$ are positive. If we assume that there is no source of disturbance situated at $z=-\infty$, the wave functions for the lower medium cannot contain terms of the forms $e^{-\alpha z}$ and $e^{-\beta z}$. Hence for the lower medium, (6) degenerate into

$$\phi'=Ee^{\alpha z},\qquad \psi'=Fe^{\beta z}. \tag{6a}$$

The stress components caused by the waves are

$$T_{zz}=\mu(\xi^2+\beta^2)\phi-2i\mu\xi\frac{\partial\psi}{\partial z} \tag{7}$$

* Note the difference in signs with the equations in the previous study. This is due to (5).

** We write sh and ch for sinh and cosh respectively.

$$T_{zz} = 2i\mu\xi\frac{\partial\phi}{\partial z} + \mu(\xi^2+\beta^2)\psi.$$

The vanishing of these at $z=H$ gives

$$\begin{aligned}(\xi^2+\beta_1^2)(A\ \mathrm{sh}\ \alpha_1H+B\ \mathrm{ch}\ \alpha_1H)-2i\beta_1\xi(C\ \mathrm{ch}\ \beta_1H+D\ \mathrm{sh}\ \beta_1H)=0\\ 2i\alpha_1\xi(A\ \mathrm{ch}\ \alpha_1H+B\ \mathrm{sh}\ \alpha_1H)+(\xi^2+\beta_1^2)(C\ \mathrm{sh}\ \beta_1H+D\ \mathrm{ch}\ \beta_1H)=0\end{aligned} \tag{8}$$

where the subscript 1 refers to the quantities appropriate to the upper medium. The continuity of stress at $z=0$ leads to

$$\begin{aligned}\mu_1(\xi^2+\beta_1^2)B-2i\mu_1\beta_1\xi C-\mu_2(\xi^2+\beta_2^2)E+2i\mu_2\beta_2\xi F=0\\ 2i\mu_1\alpha_1\xi A+\mu_1(\xi^2+\beta_1^2)D-2i\mu_2\alpha_2\xi E-\mu_2(\xi^2+\beta_2^2)F=0\end{aligned} \tag{9}$$

and that of displacement, to

$$\begin{aligned}i\xi B+\beta_1C-i\xi E-\beta_2F=0\\ \alpha_1A-i\xi D-\alpha_2E+i\xi F=0.\end{aligned} \tag{10}$$

The six equations (8), (9), (10) are homogeneous in the six constants A, B, C, D, E, F. In order that they be soluble for five independent ratios among these constants, it is necessary and sufficient that the determinant of these equations should vanish. So we must have

$$\begin{vmatrix}(\xi^2+\beta_1^2)\ \mathrm{ch}\ \alpha_1H & -2i\beta_1\xi\ \mathrm{ch}\ \beta_1H & (\xi^2+\beta_1^2)\ \mathrm{sh}\ \alpha_1H & -2i\beta_1\xi\ \mathrm{sh}\ \beta_1H & 0 & 0\\ 2i\alpha_1\xi\ \mathrm{sh}\ \alpha_1H & (\xi^2+\beta_1^2)\ \mathrm{sh}\ \beta_1H & 2i\alpha_1\xi\ \mathrm{ch}\ \alpha_1H & (\xi^2+\beta_1^2)\ \mathrm{ch}\ \beta_1H & 0 & 0\\ \mu_1(\xi^2+\beta_1^2) & -2i\mu_1\beta_1\xi & 0 & 0 & -\mu_2(\xi^2+\beta_2^2) & 2i\mu_2\beta_2\xi\\ i\xi & \beta_1 & 0 & 0 & -i\xi & -\beta_2\\ 0 & 0 & 2i\mu_1\alpha_1\xi & \mu_1(\xi^2+\beta_1^2) & -2i\mu_2\alpha_2\xi & -\mu_2(\xi^2+\beta_2^2)\\ 0 & 0 & \alpha_1 & -i\xi & -\alpha_2 & i\xi\end{vmatrix}=0. \tag{11}$$

This is a relation between ξ and ω. If we denote the apparent velocity of the wave along the surface by V_a and the apparent wave length by λ, then

$$\xi = \omega/V_a = 2\pi/\lambda.$$

Hence (11) may also be regarded as a relation between V_a and λ. The graph of this is the dispersion curve.

To facilitate discussions, let us make the following abbreviations which are slightly different from those of Love and Lee:

$$\begin{aligned}X=2\mu_2\xi^2-\mu_1(\xi^2+\beta_1^2),\quad Z=\mu_1(\xi^2+\beta_1^2)-\mu_2(\xi^2+\beta_2^2),\\ Y=2\mu_1\xi^2-\mu_2(\xi^2+\beta_2^2),\quad W=2\xi^2(\mu_2-\mu_1).\end{aligned} \tag{12}$$

Then (11) may be reduced to

$$\zeta\eta'-\zeta'\eta=0 \tag{13}$$

where

$$\begin{aligned}
\zeta &= (\xi^2+\beta_1^2)\left[(\alpha_2/\alpha_1)X \operatorname{sh}\alpha_1 H + Y \operatorname{ch}\alpha_1 H\right] \\
&\quad - 2\left[\alpha_2\beta_1 W \operatorname{sh}\beta_1 H + \xi^2 Z \operatorname{ch}\beta_1 H\right] \\
\eta' &= (\xi^2+\beta_1^2)\left[(\beta_2/\beta_1)X \operatorname{sh}\beta_1 H + Y \operatorname{ch}\beta_1 H\right] \\
&\quad - 2\left[\alpha_1\beta_2 W \operatorname{sh}\alpha_1 H + \xi^2 Z \operatorname{ch}\alpha_1 H\right] \qquad (14) \\
\zeta' &= (\xi^2+\beta_1^2)\left[(\beta_2/\xi)W \operatorname{ch}\alpha_1 H + (\xi/\alpha_1)Z \operatorname{sh}\alpha_1 H\right] \\
&\quad - 2\left[\beta_2\xi X \operatorname{ch}\beta_1 H + \beta_1\xi Y \operatorname{sh}\beta_1 H\right] \\
\eta &= (\xi^2+\beta_1^2)\left[(\alpha_2/\xi)W \operatorname{ch}\beta_1 H + (\xi/\beta_1)Z \operatorname{sh}\beta_1 H\right] \\
&\quad - 2\left[\alpha_2\xi X \operatorname{ch}\alpha_1 H + \alpha_1\xi Y \operatorname{sh}\alpha_1 H\right].
\end{aligned}$$

The calculation of the dispersion curve from (13) is quite laborious, but the correctness of the equation can be checked by considering its special cases. We notice that when H approaches zero, the formula should reduce to the Rayleigh wave equation for the lower medium. On the other hand, when H is large compared with the wave length, the interaction of the upper boundary and the interface would be slight and we should expect to obtain both the Rayleigh wave equation for the layer and the Stoneley-wave equation at the interface from (13). This is indeed the case as will be shown presently.

3. *The Simple Rayleigh Waves and the Stoneley Waves.* (i) Simple Rayleigh waves in the medium. When H approaches zero,

$$\operatorname{sh}\alpha_1 H_1, \quad \operatorname{sh}\beta_1 H \to 0; \qquad \operatorname{ch}\alpha_1 H, \quad \operatorname{ch}\beta_1 H \to 1,$$

and expressions (14) reduce to

$$\begin{aligned}
\zeta &\sim (\xi^2+\beta_1^2)Y - 2\xi^2 Z \\
\eta' &\sim (\xi^2+\beta_1^2)Y - 2\xi^2 Z \\
\zeta' &\sim (\xi^2+\beta_1^2)(\beta_2/\xi)W - 2\beta_2\xi X \qquad (15) \\
\eta &\sim (\xi^2+\beta_1^2)(\alpha_2/\xi)W - 2\alpha_2\xi X.
\end{aligned}$$

Hence (13) becomes

$$\left[(\xi^2+\beta_1^2)Y - 2\xi^2 Z\right]^2 - (\alpha_2\beta_2/\xi^2)\left[(\xi^2+\beta_1^2)W - 2\xi^2 X\right] = 0.$$

Substituting X, Y, Z, W from (12), we obtain

$$(\xi^2+\beta_2^2)^2\left[\mu_2(\xi^2-\beta_1^2)\right]^2 - 4\alpha_2\beta_2\xi^2\left[\mu_2(\xi^2-\beta_1^2)\right]^2 = 0.$$

Since $h \neq 0$, $k \neq 0$, hence $\xi \neq \beta_1$ and we have

$$(\xi^2 + \beta_2^2)^2 - 4\alpha_2\beta_2\xi^2 = 0$$

or

$$(2\xi^2 - k_2^2)^2 - (\xi^2 - h_2)^{1/2}(\xi^2 - k_2^2)^{1/2}\xi^2 = 0 \qquad (16)$$

which is precisely the simple Rayleigh wave equation for the lower medium.

(ii) Simple Rayleigh waves in the layer. When H is large compared with the apparent wave length λ,

$$\text{sh } \alpha_1 H \sim \text{ch } \alpha_1 H \sim \tfrac{1}{2}e^{\alpha_1 H}; \qquad \text{sh } \beta_1 H \sim \text{ch } \beta_1 H \sim \tfrac{1}{2}e^{\beta_1 H},$$

and (14) become

$$\begin{aligned}
\zeta &\sim \tfrac{1}{2}(\xi^2 + \beta_1^2)((\alpha_2/\alpha_1)X + Y)e^{\alpha_1 H} - (\alpha_2\beta_1 W + \xi^2 Z)e^{\beta_1 H} \\
\eta' &\sim \tfrac{1}{2}(\xi^2 + \beta_1^2)((\beta_2/\beta_1)X + Y)e^{\beta_1 H} - (\alpha_1\beta_2 W + \xi^2 Z)e^{\alpha_1 H} \\
\zeta' &\sim \tfrac{1}{2}(\xi^2 + \beta_1^2)((\beta_2/\xi)W + (\xi/\alpha_1)Z)e^{\alpha_1 H} - (\beta_2\xi X + \beta_1\xi Y)e^{\beta_1 H} \\
\eta &\sim \tfrac{1}{2}(\xi^2 + \beta_1^2)((\alpha_2/\xi)W + (\xi/\beta_1)Z)e^{\beta_1 H} - (\alpha_2\xi X + \alpha_1\xi Y)e^{\alpha_2 H}.
\end{aligned} \qquad (17)$$

Substituting in (13) and simplifying, we obtain

$$\begin{aligned}
[(\xi^2 + \beta_1^2)^2 - 4\alpha_1\beta_1\xi^2][(\alpha_2 X + \alpha_1 Y)(\beta_2 X + \beta_1 Y)\xi^2 \\
- (\alpha_2\beta_1 W + \xi^2 Z)(\alpha_1\beta_2 W + \xi^2 Z)] = 0.
\end{aligned} \qquad (18)$$

The first factor equated to zero gives

$$(2\xi^2 - k_1^2)^2 - (\xi^2 - h_1^2)^{1/2}(\xi^2 - k_1^2)^{1/2}\xi^2 = 0 \qquad (19)$$

which is the simple Rayleigh wave equation for the layer.

(iii) The Stoneley-waves. The second factor in (18) contains the material constants of both media but is independent of H. This strongly suggests a disturbance along the interface. It was actually first studied by Love[8] but is also known as the Stoneley wave.[9] To confirm this conjecture, and to facilitate comparison, we shall derive the Stoneley-wave equation by the present method, which is quite different from Stoneley's derivation.

[8] Love, *Geodynamics*, §190.

[9] R. Stoneley, *Proc. Roy. Soc. Lond A*, vol. 106, p. 416 (1924).

In Fig. 2, are shown two semi-infinite media in contact at a plane $z=0$. The problem is to find the frequency relation for the waves traveling along the interface and dying out in both directions away

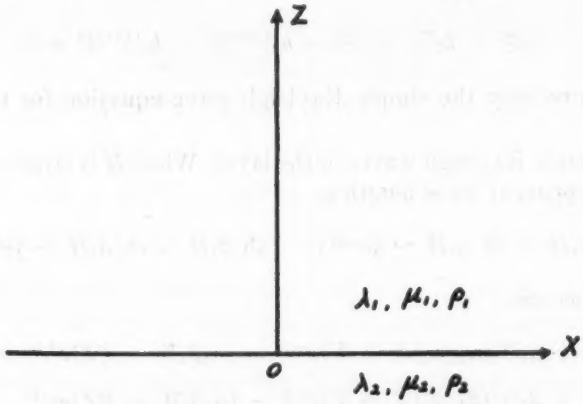

FIG. 2. Two semi-infinite media in contact at $Z=0$.

from the interface. Using the same notations as before, we proceed to solve the equations (4) under the condition that both media are semi-infinite. Then instead of (6), the solutions would be of the forms

$$\phi_1 = Ae^{-\alpha_1 z}, \qquad \psi_1 = Ce^{-\beta_1 z}$$
$$\phi_2 = Ee^{\alpha_2 z}, \qquad \psi_2 = Fe^{\beta_2 z}.$$

The continuities of the displacement and the stress at $z=0$ lead to

$$\begin{gathered}
\mu_1(\xi^2+\beta_1^2)A + 2i\mu_1\beta_1\xi C - \mu_2(\xi^2+\beta_2^2)E + 2i\mu_2\beta_2\xi F = 0 \\
-2i\mu_1\alpha_1\xi A + \mu_1(\xi^2+\beta_1^2)C - 2i\mu_2\alpha_2\xi E - \mu_2(\xi^2+\beta_2^2)F = 0 \\
i\xi A - \beta_1 C - i\xi E - \beta_2 F = 0 \\
-\alpha_1 A - i\xi C - \alpha_2 E + i\xi F = 0.
\end{gathered} \tag{20}$$

Equating the determinant of these equations to zero as before, we have

$$\begin{vmatrix}
\mu_1(\xi^2+\beta_1^2) & 2i\mu_1\beta_1\xi & -\mu_2(\xi^2+\beta_2^2) & 2i\mu_2\beta_2\xi \\
-2i\mu_1\alpha_1\xi & \mu_1(\xi^2+\beta_1^2) & -2i\mu_2\alpha_2\xi & -\mu_2(\xi^2+\beta_2^2) \\
i\xi & -\beta_1 & -i\xi & -\beta_2 \\
-\alpha_1 & -i\xi & -\alpha_2 & i\xi
\end{vmatrix} = 0. \tag{21}$$

With the abbreviations (12), it can be shown that (21) may be reduced to

$$(\alpha_2\xi X+\alpha_1\xi Y)(\beta_2\xi X+\beta_1\xi Y)-(\alpha_1\beta_2 W+\xi^2 Z)(\alpha_2\beta_1 W+\xi^2 Z)=0 \tag{22}$$

a factor $1-\alpha_1\beta_1/\xi^2$ being cancelled since $\xi^2 \neq \alpha_1\beta_1$. The left hand side of this equation is the same as the second factor in (18).

4. *The First Perturbation Due to a Thin Layer.* We have examined in the previous section two extreme cases: that of a vanishing layer or infinitely long waves and that of a very thick layer or very short waves. However, the effect of a thin, but finite layer on the behavior of the Rayleigh waves is more important. We shall calculate this effect by regarding it as a perturbation on the Rayleigh waves in the lower medium.

When H is small,

$$\operatorname{sh}\alpha_1 H \sim \alpha_1 H, \quad \operatorname{sh}\beta_1 H \sim \beta_1 H, \quad \operatorname{ch}\alpha_1 H \sim \operatorname{ch}\beta_1 H \sim 1$$

$$\therefore \quad \zeta = (\xi^2+\beta_1^2)Y - 2\xi^2 Z + [(\xi^2+\beta_1^2)X - 2\beta_1^2 W]\alpha_2 H$$

$$\eta' = (\xi^2+\beta_1^2)Y - 2\xi^2 Z + [(\xi^2+\beta_1^2)X - 2\alpha_1^2 W]\beta_2 H$$

$$\zeta' = (\xi^2+\beta_1^2)Y(\beta_2/\xi)W - 2\beta_2\xi X + [(\xi^2+\beta_1^2)Z - 2\beta_1^2 Y]\xi H$$

$$\eta = (\xi^2+\beta_1^2)Y(\alpha_2/\xi)W - 2\alpha_2\xi X + [(\xi^2+\beta_1^2)Z - 2\alpha_1^2 Y]\xi H.$$

Neglecting all terms of higher orders than the first power in H/λ, we may write (13) after simplification as

$$\begin{aligned}\zeta\eta' - \zeta'\eta = {} & [(\xi^2+\beta_2^2)^2 - 4\alpha_2\beta_2\xi^2][\mu_2(\xi^2-\beta_1^2)]^2 \\ & + \mu_1\mu_2(\xi^2-\beta_1^2)^2(\xi^2-\beta_2^2)(\alpha_2+\beta_2)H \\ & + 4\mu_1\mu_2\xi^2(\xi^2-\beta_1^2)(\xi^2-\beta_2^2)(\beta_1^2-\alpha_1^2)\beta_2 H = 0.\end{aligned}$$

Since $\xi \neq \beta_1$, this may be reduced to

$$\begin{aligned}(\xi^2+\beta_2^2)^2 - 4\alpha_2\beta_2\xi^2 + \frac{\mu_1}{\mu_2}(\xi^2-\beta_1^2)(\xi^2-\beta_2^2)(\alpha_2+\beta_2)H \\ + \frac{4\mu_1\xi^2}{\mu_2}\frac{\xi^2-\beta_2^2}{\xi^2-\beta_1^2}(\beta_1^2-\alpha_1^2)\beta_2 H = 0.\end{aligned} \tag{23}$$

Recall (5) and let γ_1 and γ_2 be the ratios of the velocities of the dilatational to those of the shear waves in the two media, i.e.,

$$V_1^2 = \gamma_1^2 v_1^2; \qquad V_2^2 = \gamma_2^2 v_2^2. \tag{24}$$

Then $\xi^2-\beta_1^2 = k_1^2$, $\xi^2-\beta_2^2 = k_2^2$, $(\alpha_1^2-\beta_1^2)/(\xi^2-\beta_1^2) = (\gamma_1^2-1)/\gamma_1^2$ and (23) is reduced to

$$\begin{aligned}&[(\xi^2+\beta_2^2)^2 - 4\alpha_2\beta_2\xi^2] \\ &\quad + H\frac{k_2^2\mu_1}{\mu_2}\left[k_1^2(\alpha_2+\beta_2) - \frac{4(\gamma_1^2-1)\xi^2}{\gamma_1^2}\beta_2\right] = 0\end{aligned} \tag{23a}$$

which is linear in H. The first term equated to zero is simply the Rayleigh-wave equation for the lower medium. Let its root be ξ_0. The effect of the second term in (23a) on its root ξ is small because H is supposed to be small. Write $\xi=\xi_0+\delta\xi$. Expanding the first term in the neighborhood of ξ_0 by Taylor's theorem, we have

$$\begin{aligned} f(\xi) &= (\xi^2+\beta_2^2) - 4\alpha_2\beta_2\xi = f(\xi_0) + (\partial f/\partial\xi)_0\delta\xi + \cdots \\ &\cong 4\xi_0\delta\xi[2(2\xi_0^2 - k_2^2 - \alpha_2\beta_2) - \beta_2\xi_0^2/\alpha_2 - \alpha_2\xi_0^2/\beta_2] + \cdots \\ &\cong 4\xi_0^3\delta\xi[4 - 2k_2^2/\xi_0^2 - 2\alpha_2\beta_2/\xi_0^2 - \beta_2/\alpha_2 - \alpha_2/\beta_2] \end{aligned} \tag{25}$$

where α_2, β_2 are to be evaluated for $\xi=\xi_0$. This root of the simple Rayleigh wave equation is generally solved in terms of k_2 which is known when the frequency of the wave and the nature of the medium are given. Let it be m so that

$$\xi_0^2 = m^2k_2^2$$

and therefore

$$\begin{gathered} \alpha_2^2/\xi^2 = (m^2 - 1/\gamma_2^2)/m^2, \qquad \beta_2^2/\xi^2 = (m^2-1)/m^2, \\ \alpha_2^2/\beta_2^2 = (m^2 - 1/\gamma_2^2)/(m^2-1). \end{gathered} \tag{26}$$

Then

$$\begin{aligned} \delta\xi\Big[4 - \frac{2}{m^2} - \frac{2}{m^2}\{(m^2-1)(m^2-1/\gamma_2^2\}^{1/2} - \left\{\frac{m^2-1}{m^2-1/\gamma_2^2}\right\}^{1/2} \\ - \left\{\frac{m^2-1/\gamma_2^2}{m^2-1}\right\}^{1/2}\Big] = -\frac{H}{4}\frac{\mu_1}{\mu_2}\Big[\frac{k_1^2}{m^2}\frac{2m^2-1-1/\gamma_2^2}{m^2} \\ - \frac{k_2^2(\gamma_1^2-1)}{\gamma_1^2}\left\{\frac{m^2-1}{m^2}\right\}^{1/2}\Big]. \end{aligned} \tag{27}$$

The expression in the bracket is known when the media are given and the simple Rayleigh wave equation for the lower medium solved.

To recapitulate, we have

(A) $(2\xi_0^2 - k_2^2)^2 - 4(\xi_0^2 - h_2^2)^{1/2}(\xi_0^2 - k_2^2)^{1/2}\xi_0^2 = 0$

(Rayleigh Wave Equation)

(B) $$\Big[4 - \frac{2}{m^2}(1+ab) - \frac{a}{b} - \frac{b}{a}\Big]\delta\xi = \frac{H}{4}\frac{\mu_1}{\mu_2}\Big[\frac{k_2^2(\gamma_1^2-1)}{\gamma_1^2}\frac{a}{m} - \frac{k_1^2}{m^2}\frac{a^2+b^2}{m^2}\Big]$$ (First Perturbation)

(C) $\xi = \xi_0 + \delta\xi$

where

$$a^2 = m^2 - 1, \qquad b^2 = m^2 - 1/\gamma_2^2. \tag{28}$$

From (B) it is seen that $\delta\xi$ is proportional to ω^2 for a given V_a, while ξ is proportional to ω. Hence (C), as a function of V_a and λ, is of the form

$$c_1 V_a^2 + \lambda = c_2 \lambda V_a$$

which is a hyperbolic arc, c_1, c_2 being constants. It should be emphasized here that the present approximation is good only when $H/\lambda \ll 1$.

5. *Discussions.* The natures of the waves depend primarily on the four parameters α_1, β_1, α_2, β_2. Our analysis so far is based on the assumption that all of them are real. Introducing the identities $\text{sh}\, ix = i \sin x$ and $\text{ch}\, ix = \cos x$ into (14), we see that the relation (13) is still real when β_1 or both α_1 and β_1 become imaginary. It is easy to see that

$$\begin{aligned} \alpha_1 H &= (2\pi H/\lambda)(1 - V_a^2/V_1^2)^{1/2}, \\ \beta_1 H &= (2\pi H/\lambda)(1 - V_a^2/v_1^2)^{1/2}, \\ \alpha_2 H &= (2\pi H/\lambda)(1 - V_a^2/V_2^2)^{1/2}, \\ \beta_2 H &= (2\pi H/\lambda)(1 - V_a^2/v_2^2)^{1/2}. \end{aligned} \tag{29}$$

For these to be real or imaginary, the criterion is determined by the value of V_a relative to V_1, v_1, V_2, v_2 which are in turn determined by the material constants of the media. The case when all these parameters are imaginary has been examined in a previous study. We are concerned here only with the Rayleigh waves and their transition to other types.

(i) *Overlying low-speed layer.* This is to approximate the weathering layer (idealized, of course). When λ (or alternatively H) is varied from 0 to ∞, V_a varies between the values of the simple Rayleigh wave velocities appropriate to the two media and which we will designate by $V(R_1)$ and $V(R_2)$. It has been shown both by Love and by Sezawa[10] that V_a increases with λ. Without making detailed calculations, we can sketch the dispersion curve as in Fig. 3. The part of the curve for large λ is asymptotic to the line $V_a = V(R_2)$. This is confirmed by the fact that this part of the curve is hyperbolic. When λ is very small, the curve starts from $V_a = V(R_1)$ according to (19). From Sezawa's results,

[10] *Op. cit.*

the curvature of this part of the curve is concave upward. This fact is of some significance as will be shown later.

The curve is drawn with the assumption that the simple Rayleigh-wave velocity in the lower medium is greater than the velocity of the distortional waves in the layer, $V(R_2) > v_1$. This is plausible because $V(R_2)$ is only slightly smaller than v_2. This being the case, the expres-

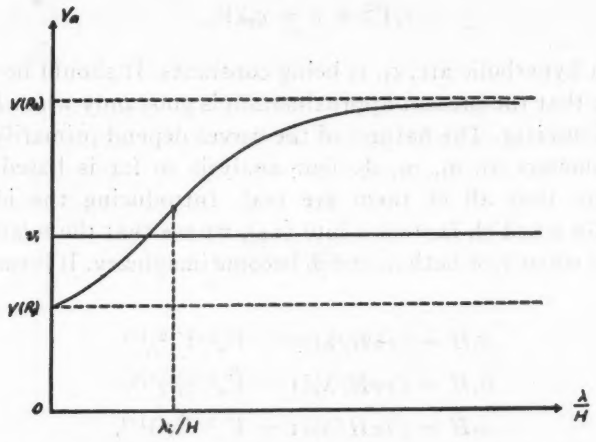

FIG. 3. Approximate dispersion curve for overlying low-speed layer.

sion of $\beta_1 H$ in (29) shows that when $V_a > v_1$, β_1 becomes imaginary. From (6), this indicates that the distortional waves will then exist only as body waves. For apparent velocities greater than v_1, the Rayleigh type of waves must be dilatational in nature. When V_a is greater than V_1, both α_1 and β_1 become imaginary, and we have only body waves. There is actually a second branch of the dispersion curves which holds for body waves only, but we need not be concerned with it here.

From (29), when V_a is increased, both α_1 and β_1 decrease (λ increases). This would mean that faster or longer waves penetrate deeper into the layer. Here, caution should be taken in the use of the notion of frequency ν defined by $\nu\lambda = V_a$. In Fig. 3, the dispersion curve shows a point of inflection at $\lambda = \lambda_i$. For wave lengths longer than λ_i, V_a increases less than a mere linear increase and longer wave means lower frequency. When $\lambda < \lambda_i$, V_a increases faster than a linear increase and longer waves means higher frequency.

A few words concerning the order of magnitudes seem to be in

place. Our approximations (16b) are based on the assumptions that $e^{\alpha_1 H} \gg e^{-\alpha_1 H}$ and $e^{\beta_1 H} \gg e^{-\beta_1 H}$. It is sufficient to discuss only the quantity

$$\beta_1 H = (2\pi H/\lambda)\left\{1 - (V_a/v_1)^2\right\}^{1/2}.$$

Since there are two variables λ/H and V_a/v_1, in this expression, accurate estimate can be made only by solving (13). However, we may get a general idea by resorting to Sezawa's work. There, it was found that when $H>\lambda$, V_a is very near to $V(R_1)$. For all the media that may possibly exist, the minimum value of $v^2/V^2(R)$ is 1.0957.[11] Let us take this value for v_1^2/V_a^2. Then $\beta_1 H = 1.857(H/\lambda)$ and we have the following table:

TABLE 1

H/λ	1	2	3
sh $\beta_1 H$	3.124	20.496	131.215
ch $\beta_1 H$	3.282	20.523	131.219
$\frac{1}{2}e^{\beta_1 H}$	3.202	20.509	131.217

Even for $H=\lambda$, the approximation is not bad and for $H=3\lambda$ the approximation is really excellent. Hence we may conclude that for a low speed layer of thickness larger than the wave length in which we are interested, the effect of the lower medium on the surface waves is insignificant.

(ii) *Overlying high-speed layer.* A well known approximation of this case is caliche overlying clay. Here the approximations (15) and (17) still hold and the dispersion curve would be of the form in Fig. 4. It starts from $V_a = V(R_1)$ when λ is very small and approaches $V(R_2)$ when λ is very large. But a point of interest is the fact that the curve would interesect the line $V_a = v_2$ at $\lambda = \lambda_c$. when $\lambda < \lambda_c$, $V_a > v_2$. From (29), β_2 will be imaginary. The physical significance of this is that no distortional waves of the Rayleigh type with wave lengths less than λ_c can exist below the lower boundary of the layer. If, further, the media are such that $V(R_1) > V_2$, there will exist a length L such that waves shorter than it can be propagated in the lower medium only as body waves. The depth of penetration is increased when the wave length is increased. But this refers to the surface waves in which the main part of the energy resides. They are usually annoying and it is the body waves which are more useful. The use of a high speed dynamite will probably help increase the efficiency of exploration through a high speed layer.

[11] C. H. Dix, *et al.*, *Quarterly of Applied Math.*, 3 (1945), pp. 151–156.

(iii) *Remarks on ground rolls and group velocity.* We do not propose to exploit here the various causes of ground rolls, but a few words concerning observation seem to be worth mentioning. On account of dispersion, what we have observed in the records as surface waves gives only the group velocity and should not be compared directly

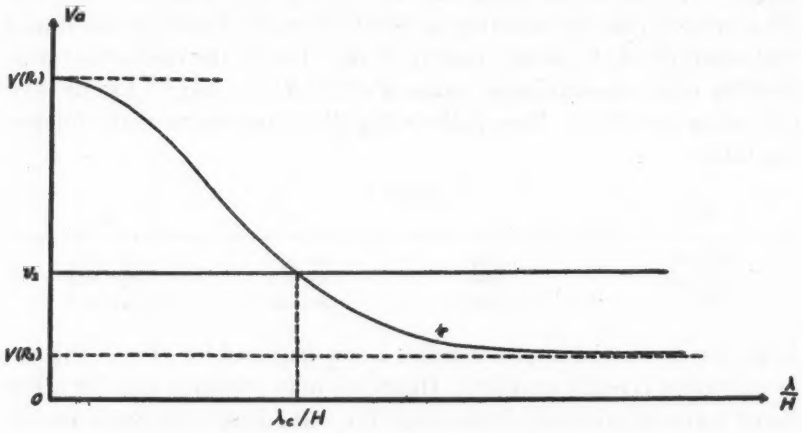

FIG. 4. Approximate dispersion curve for overlying high-speed layer.

with Fig. 3. To get the group velocity analytically from (13) is quite involved. However, we may make use of a graphical method due to Lamb[12] when the $V_a-\lambda$ curve has been calculated. At any point P on the curve in Fig. 5, let us draw the tangent. The intercept on the V-axis gives the group velocity U corresponding to λ_a. This is obvious from the definition

$$U = V - \lambda(dV/d\lambda). \tag{30}$$

According to this construction, it is seen that when V_a increases with λ, the velocity observed from the records may not do so. It depends on the curvature of the $V_a-\lambda$ curve. When it is as shown in Fig. 5, the group velocity first decreases as λ is increased. It reaches a minimum at the point of inflection $I(\lambda_i, V_i)$ and then increases with the wave length. Since this minimum group velocity is stationary with respect to the wave length, the waves corresponding to this velocity should be dominant in the record and preserve their forms.

It has often been taken for granted that the surface waves have a

[12] H. Lamb, *Manchester Memoir*, 44 (1900).

constant velocity. This would mean U=constant. From (30), it is obvious that V must then be a linear function of λ i.e.,

$$V = a + b\lambda. \tag{31}$$

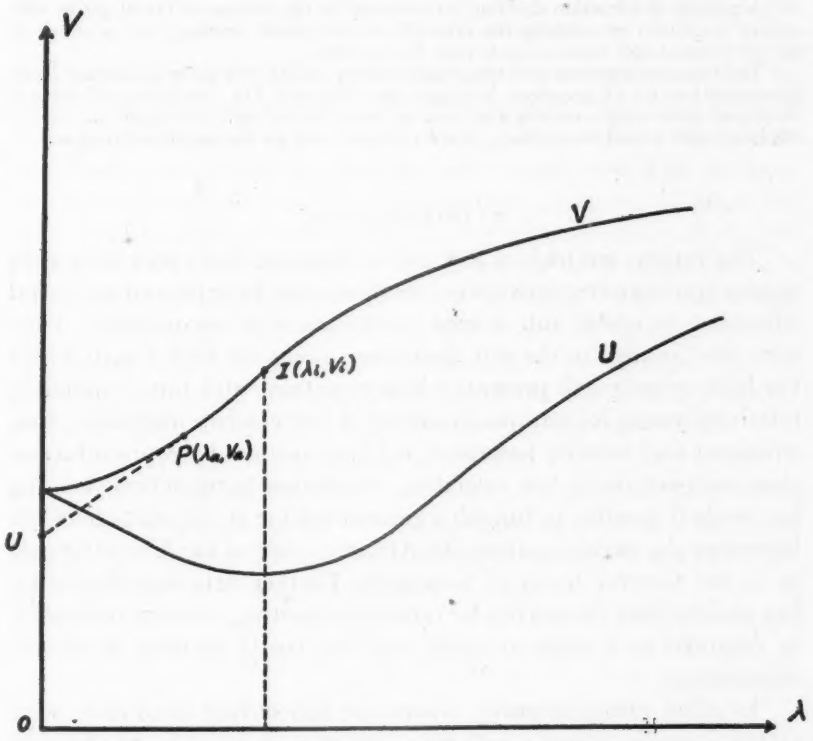

FIG. 5. Graphical calculation of group velocity.

From the dispersion curve, this is approximately satisfied when λ is in the neighborhood of λ_i where U is a minimum or when λ is very large where U and V are nearly equal.

APPLICATION OF CONTINUOUS PROFILING TO REFRACTION SHOOTING*

A. J. BARTHELMES†

ABSTRACT

A method of refraction shooting is developed for the purpose of investigating sub-surface structures by utilizing the principle of continuous profiling now generally in use for detailed and more accurate reflection surveys.

The basic assumptions and the general theory, which will allow individual depth determinations for all geophone locations, are discussed. The practical application is illustrated with sample records and cross sections. Several field techniques, as well as efficiency with regard to accuracy, production, and cost are discussed and analyzed.

A) INTRODUCTION

The various methods of Refraction Shooting of the past have been mostly applied as reconnaissance methods, and have proven successful whenever favorable sub-surface conditions were encountered. They were first applied in the salt dome area along the Gulf Coast, where the high velocity salt presents a sharp contrast with the surrounding relatively young formations consisting of low velocity materials. Also, whenever high velocity basement rocks are overlain by younger formations with relatively low velocities, correlation in refraction shooting has made it possible to furnish a general outline of the attitude of the basement; for example, along the Atlantic Coast of the United States, or in the Central Basin of Venezuela. Further detailing, thereafter, has usually been carried out by reflection shooting, which was generally regarded as a more accurate and less costly method of seismic exploration.

In other areas, however, where the sub-surface conditions were rather complex, where a reliable correlation of the refraction events from location to location could not be assured, and especially in areas where reflections could not be recorded for detailing, the need for a reliable refraction method for reconnaissance as well as detailing had arisen. This is particularly true for many areas of the Edwards Plateau in West Texas where a heavy layer of Edwards Limestone is encountered at the surface, and where reflections, so far, have not been observed. A new method has, therefore, been developed by applying to refraction shooting the principle of "Continuous Profiling," which is now generally in use for detailed and more accurate reflection sur-

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† Seismograph Service Corporation, Tulsa, Okla.

veys. This method will furnish individual depth determinations for all geophone locations, and will allow mapping of sub-surface structures continuously in the form of large traverses for reconnaissance surveys, or for any extent of detailing required.

B) ASSUMPTIONS AND REQUIREMENTS

In geologically complex areas, the actual travel path of the refracted waves can seldom be traced with sufficient accuracy to allow a mathematically correct solution. Also, these solutions, if the subsurface and its velocity distributions were known, would be too complex to be applied for routine computations. Therefore, an effort has been made to develop a simplified method which is practical and yet sufficiently accurate to meet the requirements for a reliable seismic interpretation. Some basic assumptions had to be made to simplify the calculation procedure, realizing that a certain amount of inaccuracy might be introduced, but only to such an extent that a reliable interpretation would still be allowed within the limits of the seismic accuracy desired. The following basic assumptions were made:

1) The propagation of seismic waves is based on the principle of Fermat, which states that the seismic waves follow the path which furnishes a minimum for the travel time between any two points; on Snell's law, which establishes the following relationship for a refracted wave traversing the boundary between two media:

$$\frac{\sin \gamma_i}{\sin \gamma_n} = \frac{v_i}{v_n} \qquad (1)$$

where v_i and v_n represent the seismic wave velocities and where γ_i and γ_n are the angles formed by the normal to the boundary and the trajectories in the corresponding media.

2) Refracted energies recorded on the seismic records may consist of compressional and transverse waves. Only compressional waves are considered in this paper; transverse waves as well as reverberations, will require different solutions. The seismic exploration work, so far, has been limited to the application of compressional waves.

3) The increase in refraction times observed at recording stations, with increasing distances from the shot point, are assumed to be the result of the following effects only:

a) Weathering and elevation influences t_w and t_e

b) Spread correction t_x

c) Dip effect Δt_i, caused by thickening of one, or several, zones in the overlying sediments. (Zones *a*, *b*, and *c* in Fig. 1).

The values t_w, t_s, and t_z, for all practical purposes, are independent of the dip on the refractor and can be readily determined. The value Δt_i, however, is a function of the dip and is directly related to one, or several, "zones of thickening," as shown by the shaded areas between Stations 1 and 4 in Fig. 1.

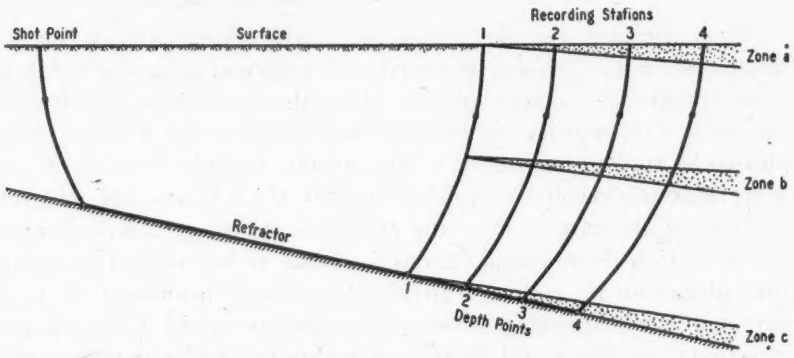

FIG. 1. Refraction wave paths, showing "zones of thickening."

4) It is assumed that the vertical velocities and their lateral changes in the geologic sections overlying the refractors are determinable, preferably by well shooting control.

It must be realized that fictitious Δt_i values may be observed as a result of local or regional changes in velocities in certain zones within the overlying sediments; for example, where a hard limestone is replaced by sand or shale. As in reflection shooting, corrections can only be applied if the sub-surface and its sedimentary changes are adequately known.

5) A constant, lateral refractor velocity is required only for "broadside" and "arc" shooting. "In-line" shooting, as further discussed below, readily reveals any change of lateral velocities in the refractors, and proper corrections can be applied.

6) The method is applicable for gentle dips as well as steep dips on the refractor, with certain limitations for steeply-dipping flank interpretations.

7) A reliable interpretation should be based on closed traverses, properly tied into one or more wells of sufficient depth, in order to be able to control the various factors affecting the dip calculations.

C) GENERAL THEORY AND APPLICATION

1) *Refraction Theory of "In-line" Shooting*

The general theory of the "Continuous Profiling" method will be

developed for the refraction procedure generally known as "In-line" shooting. The general principle of refraction shooting has been discussed in many geophysical publications, and its fundamental outline is shown in Fig. 2. The recording stations are placed at equal intervals "in line" with the shot points which are located at suitable distances

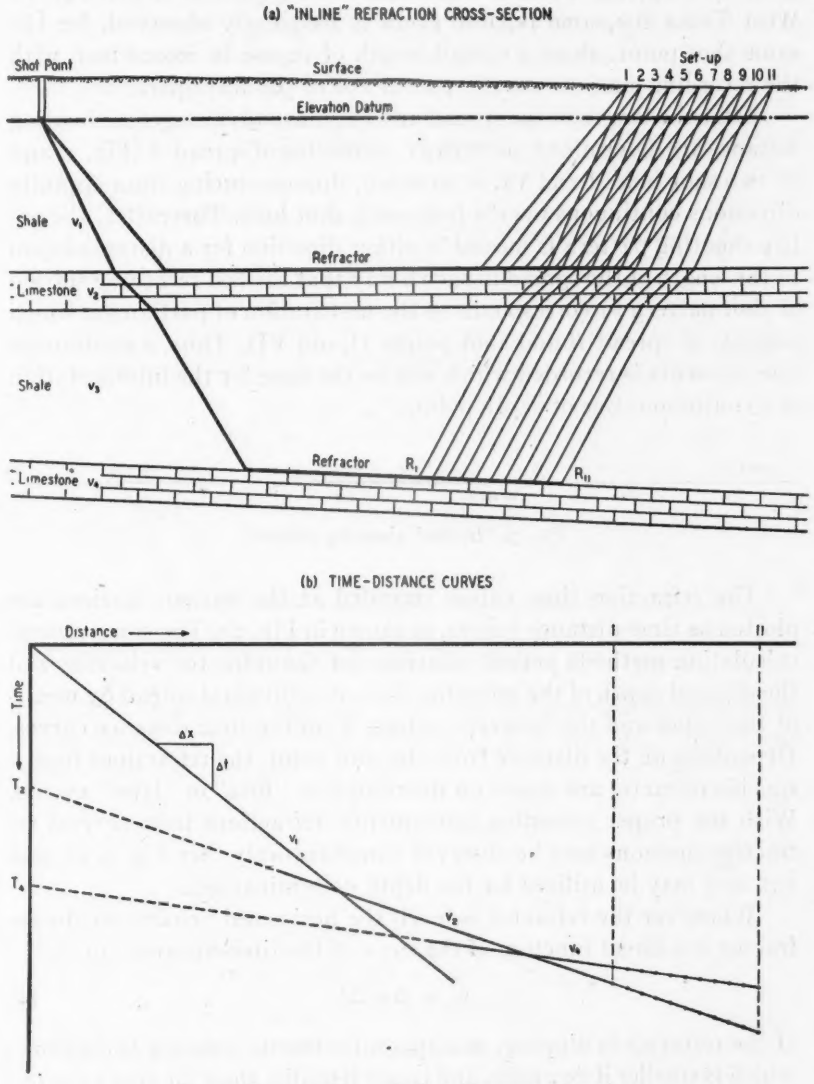

FIG. 2. Cross section and time distance curves for "in-line" refraction shooting.

from the set-up of the recording stations. Each area and each refractor produce the best results for a certain spread distance from the shot point, which may vary widely, depending on the geologic conditions in different areas. The distance and the length of the spread, which will produce the same continuous events, are determined at the beginning of the survey, and the most suitable shooting pattern is laid out. In West Texas the same reliable event is frequently observed, for the same shot point, along a spread length of 10,000 to 20,000 feet, with the recording stations usually placed 250 to 500 feet apart.

After the length of the spread and the most advantageous shooting distance are determined, pattern #1, consisting of spread *A* (Fig. 3) and its two shot holes I and VI, is recorded, thus producing from opposite directions continuous events from each shot hole. Thereafter, the entire shooting pattern is moved in either direction for a distance equal to the length of the spread in such a way that the last recording station of shot pattern #1 corresponds to the first station of pattern #2, which consists of spread *B* and shot points II and VII. Thus, a continuous line of events is recorded which will be the base for the interpretation of a continuous line of depth points.

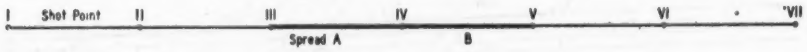

FIG. 3. "In-line" shooting pattern.

The refraction time values recorded at the various stations are plotted as time-distance curves, as shown in Fig. 2b. The conventional calculation methods permit solutions for the refractor velocities and the dip and depth of the refractors for any individual spread by means of the slopes and the intercept values, *T*, of the time-distance curves. Depending on the distance from the shot point, the refractions from a specific refractor are shown on the records as "first" or "later" events. With the proper recording instruments, refractions from several refracting horizons may be observed simultaneously (See Fig. 9, 11, and 13), and may be utilized for the depth determinations.

Whenever the refractor is level, the horizontal velocity in the refractor is a direct function of the slope of the time-distance curve,

$$v_n = \Delta x/\Delta t. \qquad (2)$$

If the refractor is dipping, an apparent refractor velocity is obtained, which is smaller if downdip, and larger if updip, than the true velocity. By shooting reversed profiles the true refractor velocity may be de-

termined, and the dip and depth of the refractor may then be calculated, as illustrated in various text books.

2) *Weathering and Elevation Corrections*

The refraction time values recorded at successive recording stations of the set-up are first corrected for weathering and elevation influences. These corrections will reduce the observed travel time (t_r) to a corrected, or theoretical, travel time (t_c) which would be observed if the shot depth and the recording stations were located at the level of the elevation datum,

$$t_c = t_r - \sum t. \tag{3}$$

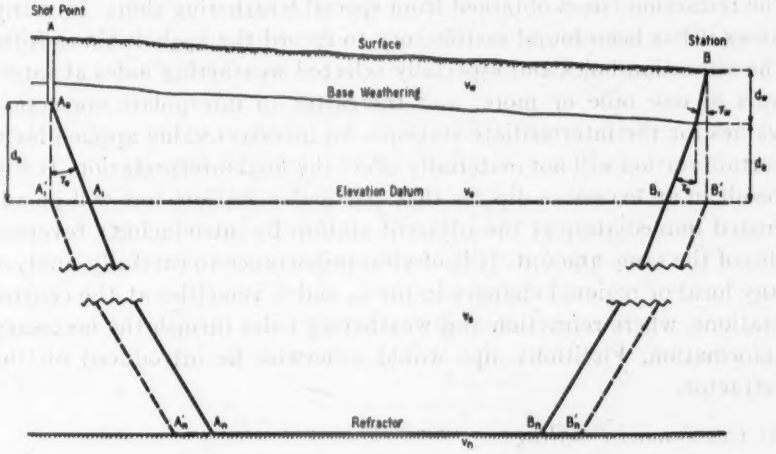

FIG. 4. Refraction cross section.

Thus, the actual travel path A_0–A_1–A_n–B_n–B_1–B is replaced by a theoretical travel path A_1'–A_n'–B_n'–B_1' (See Fig. 2 and 4). The Shot Point correction is

$$t_s = A_0A_1/v_s - A_nA_n'/v_n$$

where

$$A_0A_1 = d_s/\cos\gamma_s \text{ and } \sin\gamma_s = v_s/v_n,\ \cos^2\gamma_s = 1 - v_s^2/v_n^2$$

$$A_nA_n' = A_1A_1' = d_s \tan\gamma_s$$

$$t_s = d_s/(v_s\cos\gamma_s) - d_s\tan\gamma_s/v_n$$

$$t_s = d_s/(v_s\cos\gamma_s)[1 - (v_s/v_n)\sin\gamma_s]$$

$$t_s = d_s/(v_s\cos\gamma_s)[1 - v_s^2/v_n^2] = d_s(v_s\cos\gamma_s)\cos^2\gamma_s$$

$$t_s = (\cos\gamma_s/v_s)d_s$$

The station correction (as derived above) is

$$t_w = d_w \cos \gamma_w / v_w \quad \text{and} \quad t_e = d_e \cos \gamma_e / v_e.$$

The total correction is, therefore

$$\sum t = (t_w + t_e) + t_s$$

$$\sum t = d_w \cos \gamma_w / v_w + [d_e + d_s] \cos \gamma_e / v_e. \tag{4}$$

The weathering velocity (v_w) and the elevation velocity (v_e) must be accurately determined by up-hole times recorded in the refraction holes and in intermediate weathering holes wherever necessary. The correction values for the individual stations may be calculated from the refraction times obtained from special weathering shots. In many areas it has been found satisfactory to record the up-hole times from the refraction holes and especially selected weathering holes at intervals of one mile or more, and thereafter to interpolate correction values for the intermediate stations. An incorrect value applied for a certain station will not materially affect the final interpretation. It will result in an excessive dip for that particular station, but will be adjusted immediately at the adjacent station by introducing a reversed dip of the same amount. It is of vital importance to carefully analyze any local or regional changes in the v_w and v_e velocities at the control stations, where refraction and weathering holes furnish the necessary information. Fictitious dips would otherwise be introduced on the refractor.

3) *Continuous Profiling*

The method of "Continuous Profiling" is based on the general refraction theories outlined above. Assuming that the depth point for a certain recording station is established; for example, depth point (R_1) for Station #1 in Fig. 2a, the relative position of the adjacent depth point (R_2) can be calculated from the refraction times of Stations Nos. 1 and 2. The process of individual trace analysis on the refraction record, after applying proper corrections for weathering and elevations, furnishes time intervals Δt_c observed between adjacent stations.

Assuming that the true refractor velocity (v_n) is already determined, the corrected value Δt_c between two stations is

$$\Delta t_c = t_z = \Delta x / v_n \tag{5}$$

whenever the refractor is level. The value t_z is called the spread cor-

rection and has been shown as recorded between Stations Nos. 2 and 3, (Fig. 5). The dip effect (Fig. 1) is

$$\Delta t_i = \Delta t_c - t_x. \tag{6}$$

However, if the value Δt_c is larger or smaller than the spread correction, the variation Δt_i can be expressed as a function of the dip on the refractor, created by a "zone of thickening," as illustrated in Fig. 1. If the refractor has an updip, as shown between Stations Nos. 1 and 2, the time interval Δt_c is smaller than the spread correction t_x; for downdip conditions as suggested between Stations Nos. 3 and 4, the Δt_c value is larger than the spread correction.

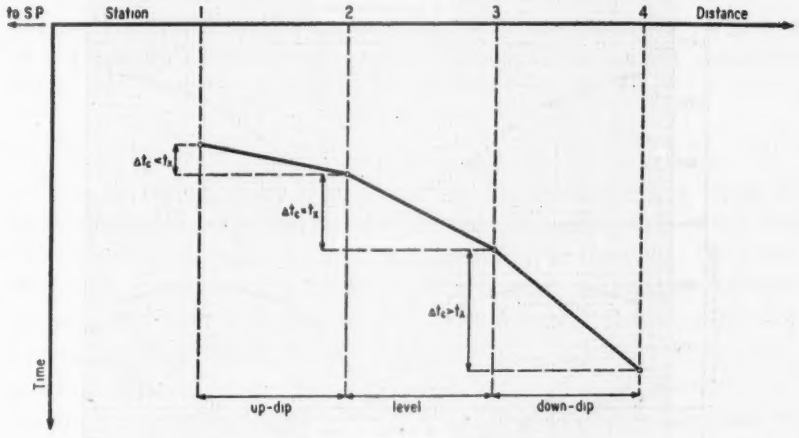

FIG. 5. Trace analysis.

The true refractor velocity is readily calculated by averaging a large number of Δt_c values which have been observed for the same refractor section from opposite holes, by applying equation 5.

The practical application of "Continuous Profiling" and the construction of the refractor are illustrated in Fig. 6 for an idealized four-station set-up.

The recording stations of the two set-ups *A* and *B* are assumed to receive refracted energy from the same section 1-2-3-4 of the refractor, as shown in Fig. 6a. Set-up *A* is recorded from Shot Hole II located towards the right; Set-up *B* from Shot Hole I located towards the left.

Fig. 6b shows the time-distance curves and the construction of the refractor, as follows:

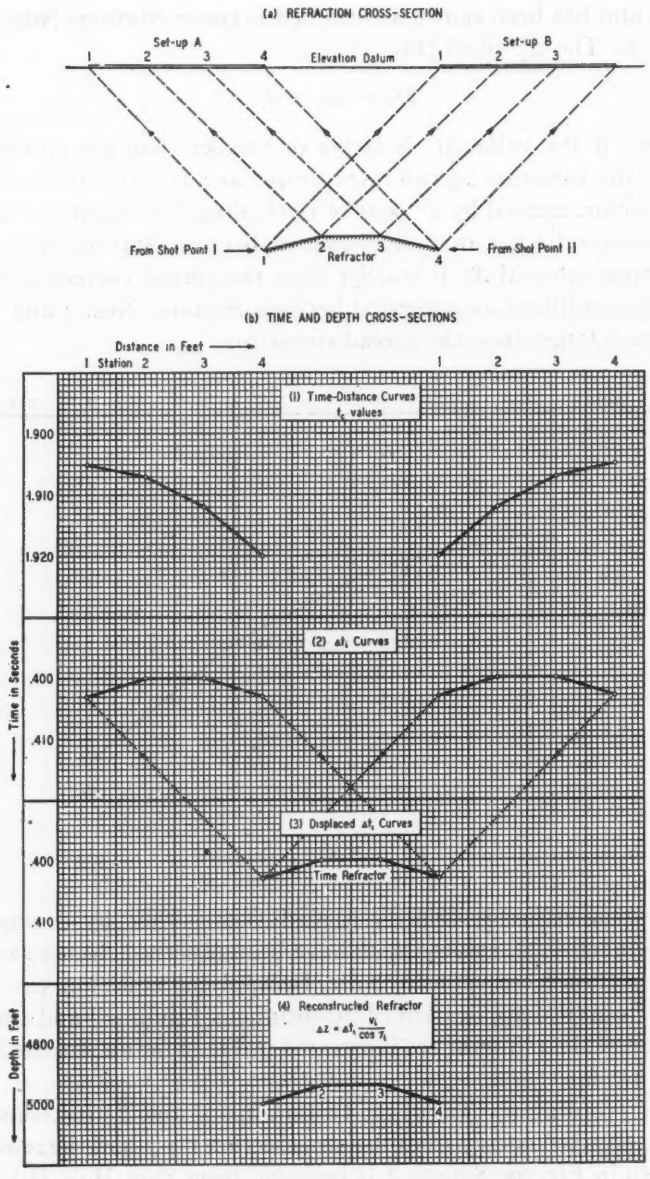

FIG. 6. Idealized set-up.

1) The corrected time values (t_c) are plotted as time-distance curves below their respective recording stations, and the Δt_c values are calculated.

2) The spread correction (t_z) ix applied to the Δt_c values to construct the Δt_i curves (equation 6). Assuming that the time-depth of a base station (for example, Depth Point No. 1 of the refractor) is already determined, successive Δt_i values are applied to the time-depth value for Station No. 1, thus independently developing the Δt_i curves for the two set-ups.

3) The two Δt_i curves are properly displaced to the original depth point location on the refractor. Since the Δt_i curves do not always coincide because of the inaccuracies inherent to the methods applied, an average Δt_i curve is constructed by averaging the two time values of the time refractor for each individual station (See also Fig. 9).

4) The depth of the refractor is constructed by converting the averaged time values of the time refractor into depth in feet by means of a time-depth conversion factor which shall be further discussed below.

4) *Dip Determination*

The Δt_i value which is presumed to be the effect of a "zone of thickening," is used to compute the increase in depth (Δz) between two adjacent stations. It is assumed that the refractor is level at the point of refraction, which will allow a practical and sufficiently reliable solution. The velocity v_i in the "zone of thickening," if not established by well shooting control, must be estimated. The dip Δz between depth points R_1 and R_2, as shown in Figs. 2 and 7, may then be calculated. If no dip were present, the time increase at Station No. 2 would amount to

$$t_z = R_1R_2''/v_n = \Delta x/v_n.$$

If a dip exists between the depth points of Stations 1 and 2, it is assumed that the wave which is refracted at R_2 travels through the refractor close to the level $R_1'R_2'$, therefore

$$\Delta x = R_1R_2'' \sim R_1'R_2'.$$

Thus the time-dip variation may be expressed:

$$\Delta t_i = \Delta s/v_i - \Delta \bar{x}/v_n.$$

Since

$$\sin \gamma_i = v_i/v_n \text{ (Snell's Law)} \quad \text{and} \quad \cos^2 \gamma_i = 1 - v_i^2/v_n^2$$

$$\cos \gamma_i = \Delta z/\Delta s \qquad \tan \gamma_i = \Delta \bar{x}/\Delta z$$

$$\Delta s = \Delta z/\cos \gamma_i \qquad \Delta \bar{x} = \Delta z \tan \gamma_i$$

Therefore,

$$\begin{aligned}\Delta t_i &= \Delta z/(v_1 \cos \gamma_i) - \Delta z \tan \gamma_i/v_n \\ &= (\Delta z/\cos \gamma_i)\left[1/v_i - \sin \gamma_i/v_n\right] \\ &= (\Delta z/\cos \gamma_i)\left[1/v_i - v_i/v_n^2\right] \\ &= (\Delta z/v_i \cos \gamma_i)\left[1 - v_i^2/v_n^2\right] \\ &= (\Delta z/v_i \cos \gamma_i) \cos^2 \gamma_i \\ &= \Delta z \cos \gamma_i/v_i \\ \Delta z &= \Delta t_i v_i/\cos \gamma_i. \qquad (7)\end{aligned}$$

The value $v_i/\cos \gamma_i$ in equation (7) is the time-depth conversion factor, which is considerably larger than the factor to be applied for reflection shooting ($v_i/2$). Values of 15 to 25 feet for each .001 of a

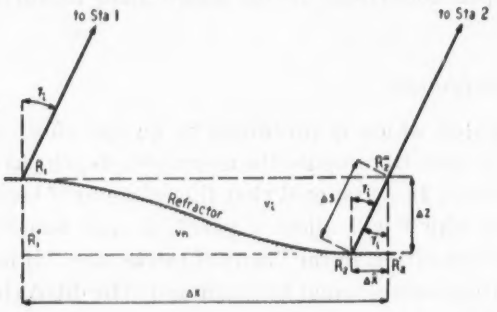

FIG. 7. zone of thickening.

second are not uncommon in refraction shooting and illustrate the reduced limits of the accuracy generally recognized in refraction shooting.

The extremely practical solution presented by equation (7) is mathematically correct to calculate the true amount of relief between the "highs" and the "lows" of a structural interpretation, independent of the steepness of dip that may be present along the flanks of the structures. However, the depth points, located on the flanks of a structure and constructed from the Δt_i curves recorded from opposite directions, do not coincide closely because of the difference in displacement of the depth points for up-dip and down-dip shooting (See Fig. 9). They will shift toward the low areas for either direction of shooting. This shift will not seriously affect gentle dips up to 10 degrees, but should be recognized for steeper dips, since it will result in broadening the "highs" and narrowing the "lows." Years of practical

experience have shown that, if the limitations are properly recognized, the simple and practical solution presented in this paper will allow a reliable interpretation of refraction data.

5) *Depth and Displacement of the Refractor*

The refractor depth can be accurately determined only when suitable geologic conditions allow a reliable identification of it; i.e., if massive refractor formations are separated by large bodies of sand or shale, or other low velocity materials that will make an absolute identification possible. The accurate depth may be obtained most reliably if a deep hole is available, which will furnish reliable well data which may be utilized for the depth of the base point (R_0).

The absolute depth of the individual depth points (R_n) is obtained by adding their respective Δz values to an original base point (R_0), the depth of which must first be determined.

Some information about the vertical velocity distribution is essential for all calculations. The identification may be easily checked by utilizing the time-distance curve for a level section of the refractor (See Fig. 2b). The following equation, given in various text books, will furnish an approximation for checking purposes

$$z = (T/2)(v_a/\cos \gamma_a) \tag{8}$$

where v_a represents the average velocity to the refractor and T is the intercept time. If reliable interval velocities are available from a well shooting test, conventional depth calculations for multiple layer conditions, either straight line or curved path solutions, may be applied.

The displacement (x) of the refractor (See Fig. 8) is calculated from the thickness of the various formations (Δz), and their respective velocities (v_i) by applying Snell's Law:

$$x = \sum \Delta x_i = \sum \Delta z_i \tan \gamma_i. \tag{9}$$

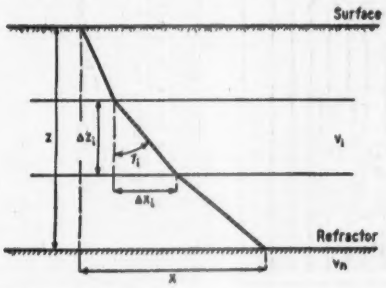

FIG. 8. Displacement of depth point.

The calculated displacement may be checked by comparing the Δt_i curves from opposite shooting. The maxima and minima of the

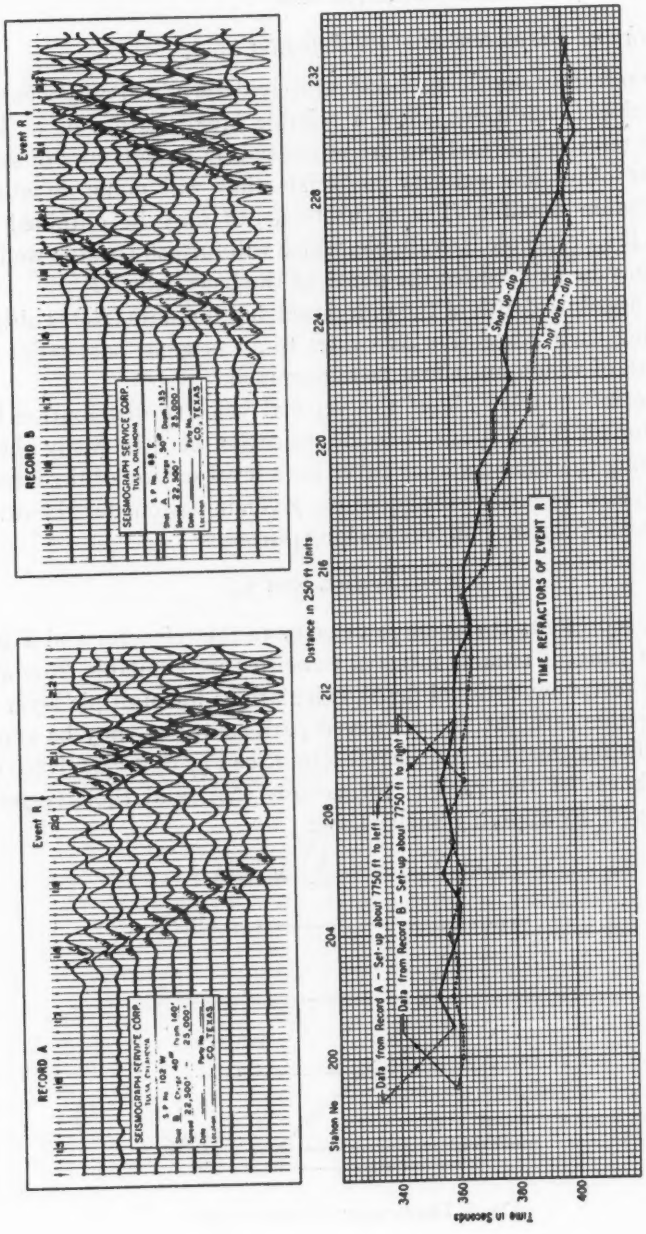

FIG. 9. "In-line" refraction records and displaced Δt_i curves.

Δt_i curves, if properly displaced, should occur at the same locations.

Displaced Δt_i curves were calculated from two "In-line" refraction records (*A* and *B* in Fig. 9). The outstanding event "*R*," which is marked on the records observed at set-ups about 12,500 feet apart, originated from approximately the same section of the refractor. It should be noted that the two Δt_i curves, which were plotted with the same displacement for all stations, agree closely whenever the refractor is level, as shown at both ends of the sample cross section. However, because of certain inaccuracies inherent to the simplified solution, the two curves move somewhat apart toward the lower end of a flank. An average of the two curves is, in most cases, sufficient for a reliable interpretation and will furnish the Δt_i values for the time-depth conversions.

D) FIELD METHODS AND EFFICIENCY

"In-line" Shooting

All refraction surveys should be started with base lines, which are carried out as "In-line" shooting. It is the most reliable, but also the most expensive method since each set-up has to be shot twice from opposite holes (See Fig. 3). The "In-line" shooting method furnishes values for the true velocities and their lateral changes in the refractor; it allows the identification of the refractors, and the calculation of their depths and displacements. Further detailing in the area, thereafter, may be carried out by one of the following methods:

"Broadside" Shooting

The most favorable shooting distance as established from the base lines is selected for the shot points which are located at right angles to

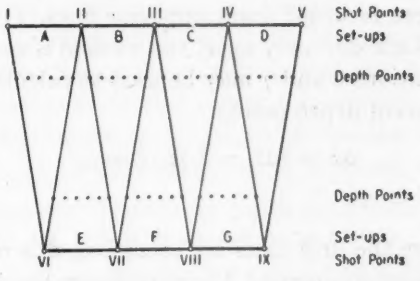

FIG. 10. "Broadside" surface plan.

the set-up (Fig. 10). This method requires a uniform refractor velocity across the entire area to be surveyed, since time variations due to velocity changes would be interpreted as dips on the refractor. Set-up

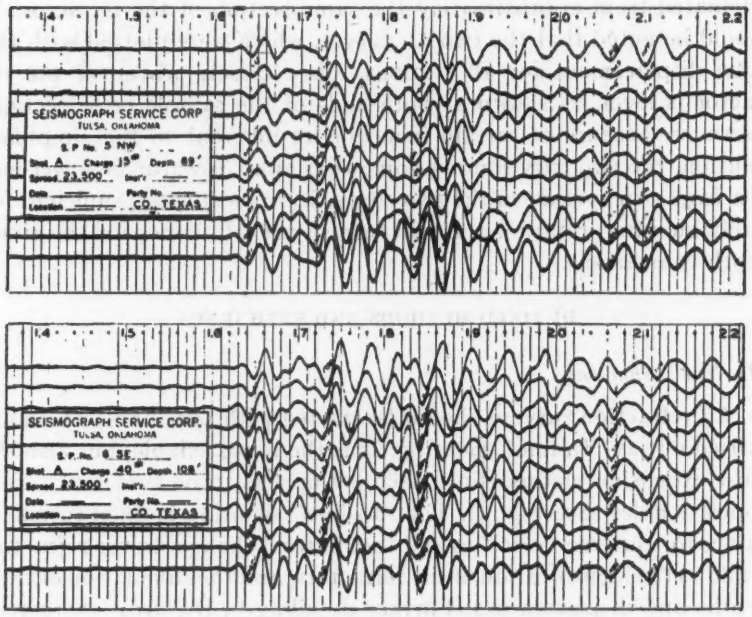

FIG. 11. "Broadside" refraction records.

A is recorded from Shot Point VI; Set-up *B* from Shot Point VII, and so on. Thereafter, the recording and shooting positions are reversed, and Set-up *E* is recorded from Shot Point II; Set-up *F* from Shot Point III, and so on. Some typical refraction records are shown in Fig. 11; they were recorded from opposite lines, 23,500 feet apart. Since the spreads are shot only once, the method is considerably more economical. Equations 6 and 7 may be used to calculate the refractor dip between adjacent depth points.

$$\Delta z = (\Delta t_e - t_z)v_i/\cos \gamma_i. \tag{10}$$

"Arc" Shooting

In areas where the drill costs are excessive, this method has been found to be the most economical. The most favorable shooting distance is selected as radius for the arcs around the shot points. All set-ups are

shot only once, and a spread correction is not required. As shown in Fig. 12, a minimum of shot holes is required for this shooting pattern, which may be extended in all directions. The refractor dip between adjacent depth points is obtained from Equation 7. Since $\Delta t_i = \Delta t_c$, this equation may be modified as follows:

$$\Delta z = \Delta t_c v_i / \cos \gamma_i. \qquad (11)$$

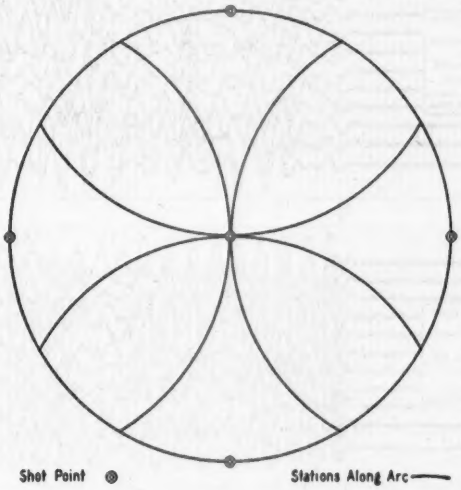

FIG. 12. "Arc" surface plan.

Three typical "Arc" refraction records are shown in Fig. 13; they also illustrate character changes frequently observed in the same area. The event "*R*," which was carried continuously along Arc No. 2, is shown as a first trough refraction on Record B, while Record C shows the same event as a second trough refraction.

It is generally recognized that refraction shooting, if compared with reflection shooting, has a greatly reduced *accuracy* which will not allow the evaluation of small anomalies. However, the method is of great value in investigating large-sized anomalies and regional dips over wide areas. The reduced accuracy is the result of several factors:

1) The lack of control over the travel path with regard to vertical and greatly extended lateral distances.
2) The fact that two depth points enter into the travel path calculations. In "Broadside" and "Arc" shooting, special adjust-

ments must be made to compensate for the change of dip introduced by the depth point variations on the shot point side.

3) The time depth conversion factor is two to five times as large as applied for reflection shooting.

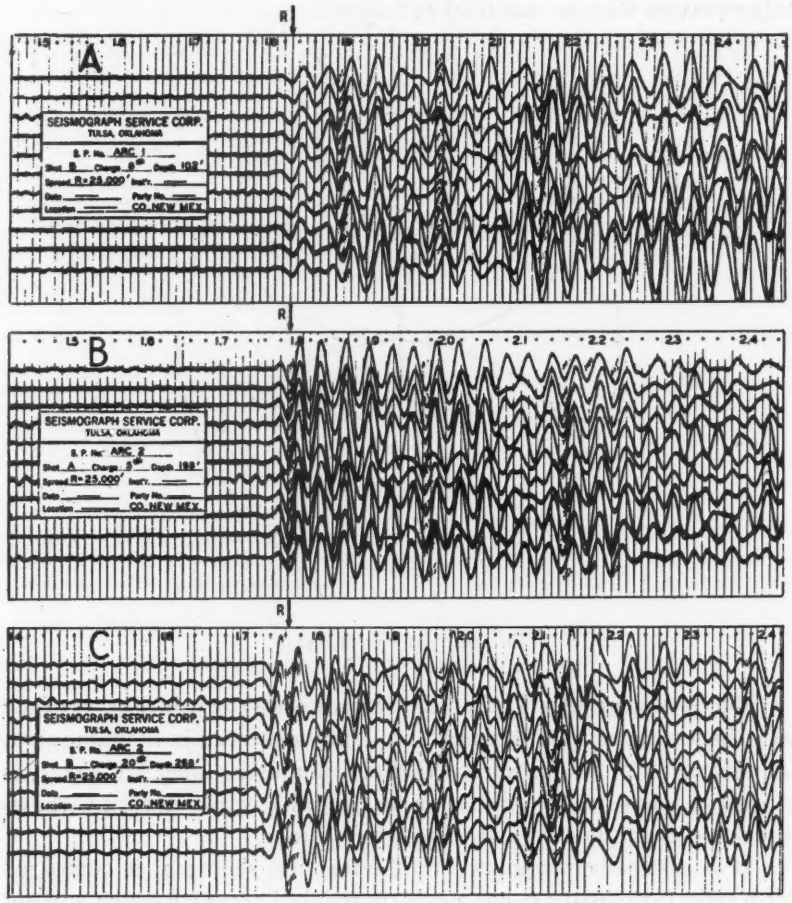

FIG. 13. "Arc" refraction records.

The *production* in refraction shooting varies widely, depending on the surface conditions and also on the depth of the refractors. The use of "later" events has greatly reduced the dynamite charges, which in some areas are comparable to those in reflection shooting. A well-experienced party with equipment corresponding to a standard re-

flection party consisting of only one shooting truck and one instrument truck, will cover about two to three miles of continuous profiling per day. This production, which is equivalent to the production generally achieved by reflection shooting, may be increased considerably by the addition of a second shooting truck or a second instrument truck and a cable truck.

The *cost* of refraction shooting, if based on continuous profiling, is actually not greatly different from the cost generally expected for reflection shooting, the cost of which varies widely depending on the shooting conditions. Many years of refraction experience show that the cost of refraction shooting in some areas may be as low as the average cost of a reflection party, or may show an increase up to 100 per cent in the areas where unfavorable shooting conditions are encountered.

The surveying and recording costs are generally similar to those observed in reflection shooting. The dynamite charges are generally somewhat higher because of the great travel distances required, though they have now been greatly reduced because of improved instruments and the use of "later" events. Two to ten pound charges have been sufficient in some good shooting areas to produce multiple events at distances of 30,000 feet, to various depths down to 8,000 feet, while in other areas charges of a few hundred pounds might be required.

It has been recognized that wherever an increase in cost was observed, it occurred mainly in the drilling cost, which occasionally amounts to more than 50 per cent of the total cost. Since refraction shooting is frequently applied in areas where reflections are not observed because of limestone outcrops, the drilling in these areas is always the dominating cost item. If reflection shooting could be carried out in these areas, its cost would be equally high, or may be even higher than for refraction shooting, because of the large number of holes required.

The application of "Continuous Profiling" to refraction shooting, especially in areas where reflections cannot be obtained, has resulted in the development of a method for reconnaissance and detailing which is sufficiently accurate, and also economical with regard to production and cost.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Seismograph Service Corporation for permission to publish this paper.

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THE CORRELATION REFRACTION METHOD OF SEISMIC SURVEYING*

J. A. GILLIN† AND E. D. ALCOCK†

ABSTRACT

This paper presents a method of refraction shooting which has been developed to solve the problem of obtaining seismic data in the Edwards Plateau region of West Texas. The results of an experimental survey in the Todd Area, Crockett County, Texas, are shown to illustrate the method.

INTRODUCTION

It is not uncommon in seismic surveying to encounter areas in which the standard reflection methods fail to produce results. Such areas present a problem and a challenge to the geophysicist. Most of the uncomplicated areas have been surveyed one or more times with the seismograph, while the problem areas represent virgin territory for exploration, and as such, warrant the expenditure of considerable time and effort in their solution.

The causes for the failure of the standard reflection methods are many, such as surface conditions, discontinuities in the subsurface, lateral changes in velocities, etc. Due to the diversity of conditions which can cause the failure of the standard reflection methods, each problem area must be considered as an individual case and be analyzed from the standpoint of those conditions which are thought to cause the failure of the standard reflection methods. In some cases the problem can be solved by some variation in the standard reflection techniques, while in other cases it is necessary to resort to other techniques.

An outstanding example of an area, the major portion of which, to the present time, has proved unsuitable for the standard reflection methods or any variation thereof, is the Edwards Plateau in West Texas. (See Fig. 1.) This statement does not imply that some portions of the Plateau cannot be surveyed by reflections. It is thought at the present time that the main cause for the failure of the reflection method here is the presence on the surface of a thick section of hard lime (Edwards lime). It is known that in those parts of the Plateau where the lime section is thin or absent entirely, and to the south of

* Presented at the fourteenth annual meeting, Dallas, Texas, March, 1944.

† National Geophysical Company, Dallas, Texas.

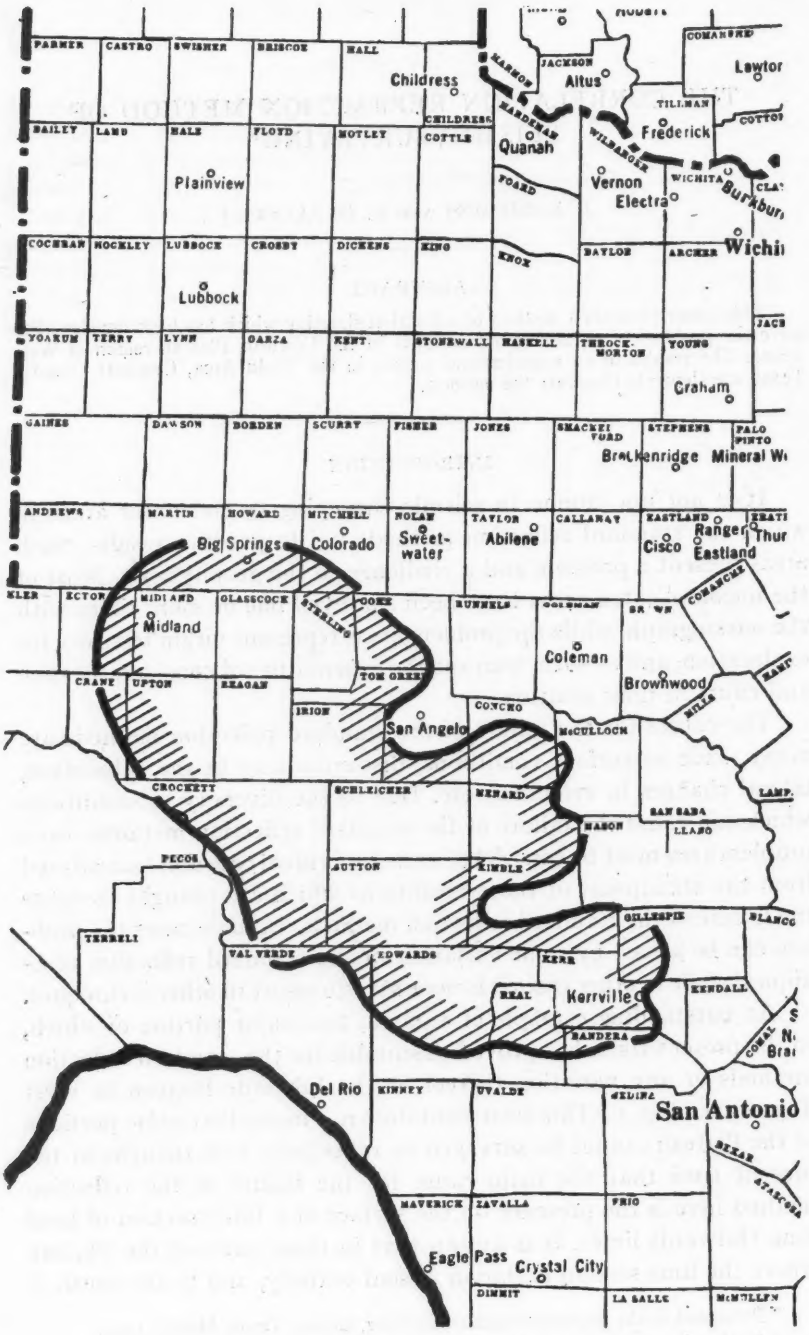


FIG. 1. Approximate limits of the Edwards Plateau.

the Plateau where the lime is buried by a blanket of younger sediments, it is possible to use successfully the reflection method.

One method which has been developed to solve the problem of obtaining subsurface seismic data on the Edwards Plateau has been called the Correlation Refraction Method. The Method is based upon the interpretation of the recorded arrivals of energy traveling from the shot point to instruments along refracted paths. The interpretation is not necessarily confined to one horizon, since the recordings are made in such a manner as to register not only the first arrival of refracted energy but all subsequent arrivals as well.[1]

CORRELATION REFRACTION SHOOTING

From the fundamental seismic theory it is known that at any given distance between shot point and instrument spread, sufficiently large, there will be a number of arrivals of refracted energy. For every shooting distance and velocity distribution there is a depth of penetration of refracted energy. All refracting horizons located between the surface and this limiting depth will refract energy which will be recorded at the given shooting distance. (See Fig. 2.) The number of arrivals, then, will depend upon the shooting distance and the number of refracting horizons in the subsurface located between the surface and the depth of penetration. The order of the arrivals will depend upon the shooting distance, depths, dips and velocities of the refracting horizons. Theoretically, then, it is possible to make an interpretation of all the refracting horizons in the subsurface down to the depth of penetration using only one distance between shot point and instrument spread. In practice there is an optimum shooting distance for any given refracting horizon. While it is possible to interpret all refractions registered on the recording, the interpretations will not be as accurate as that based upon the refraction for which the shooting distance is an optimum.

In the early refraction shooting the interpretation was confined in general to the first arrivals of refracted energy. The instruments used were of a low-frequency, undamped type, which gave a more accurate measurement of the initial arrival of energy but which possessed little or no resolution for the recording of subsequent arrivals of refracted energy. Interpretations based on initial arrivals demand continuous recording over a long distance, which is a rather slow and expensive

[1] Also see G. A. Gamburtsev, "Correlation Method for the Registration of Refracted Waves," *Bull. Acad. Sci. U.R.S.S.*, Ser. Geog. Geophys., Moscow, No. 1/2, 26–47, 1942. (Summarized, pages 59–65, this issue.)

procedure. Moreover, there are cases where, due to the arrangement of velocities and the separation of the horizons, the energy refracted along a horizon will never appear as an initial arrival. An example would be the case where a refracting horizon, at depth, of one velocity is immediately underlain by another refracting horizon of much greater

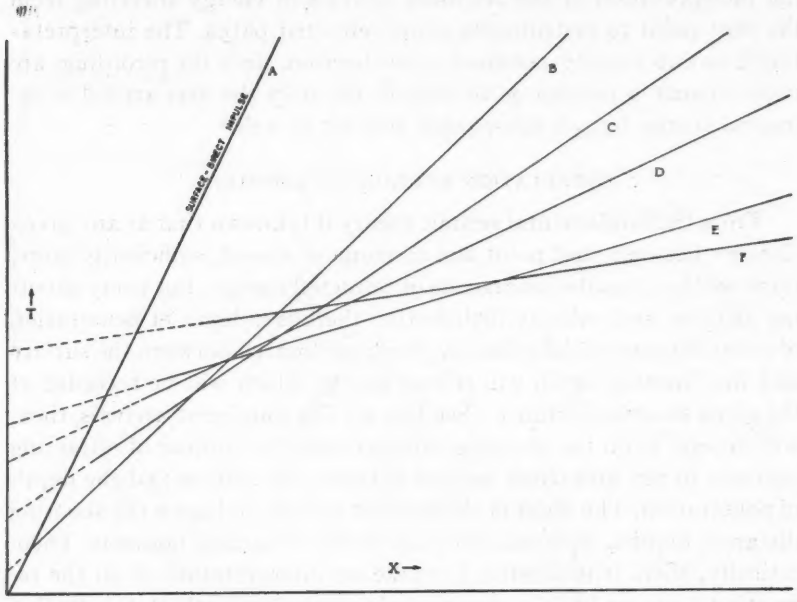


FIG. 2. Time-distance curves for refracted waves from layers of successively higher velocities and also at successively greater depths ($V_A<V_B<V_C<V_D<V_E<V_F$; $D_A<D_B<D_C<D_D<D_E<D_F$).

velocity; in such a case the first horizon would never appear as an initial arrival, and would never be accounted for in the interpretation. An example is horizon *D* of Fig. 2.

By using the customary reflection instruments, sufficient resolution can be obtained to observe not only the initial arrival of energy but subsequent arrivals of refracted energy as well. It is true that this type of instrument does not generally give a good recording of the exact time of the initial arrival of energy; however, a later phase (usually the first trough of the refracted impulse) can be used in the interpretation without introducing any appreciable error in the relative picture.

If the recordings are made with instruments having adequate resolution it is possible to make an interpretation for several refracting

horizons using only one shooting distance. It should also be noted that a much shorter shooting distance can be used for the interpretation of a deep refracting horizon than is required by the conventional refraction shooting. This is true since it is not necessary for the energy refracted alone the deep horizon to appear as an initial arrival. The combination of a shorter shooting distance and the use of reflection instruments greatly reduces the amount of energy required to produce a good recording. The reduction in energy and the limiting of the recording to one shooting distance at each point result in a considerable saving in the use of explosives, one of the major factors in the cost of refraction shooting.

If a series of recordings is made in an area from a series of shot points all at the same shooting distance, it is generally possible to correlate the arrival times, on the series of recordings, of energy from the same refracting horizons by use of the proper criteria. The criteria are time of arrival, character of the impulse, and the horizontal velocity of the refracting horizon as indicated by the "step-out" on the record.

It should be noted that the correlation of reflected impulses is made by using only two criteria—namely, time of arrival and character of impulse—whereas in the correlation refraction work an additional criterion, the "step-out" time, is available to check the correlation. For an example of the type of recording obtained by this method and the correlation possibilities, see Fig. 3. These figures present four recordings from widely separated areas on the Edwards Plateau and show a marked similarity in both appearance (i.e. character) of the refraction and in "step-out" times.

If it is now assumed that there are no lateral changes in either horizontal or vertical velocities, any observed difference in the time of arrival of refracted energy from a given refracting horizon can be related to the change in depth of the horizon. It is true that such a difference in the time of arrival is due to two factors; (1) change of depth under the shot point and (2) change in depth under the instrument spread. If it is now assumed that the refracting horizon is a plane, the difference in arrival time can be directly related to the depth of the refracting horizon at approximately the midpoint of the shooting distance. There are methods for the determination of the depth under the shot point and under the instrument spread. One such method was presented in a paper by L. W. Gardner.[2]

[2] L. W. Gardner, "An Areal Plan of Mapping Subsurface Structure by Refraction," GEOPHYSICS, Vol. VII, No. 2, April 1942.

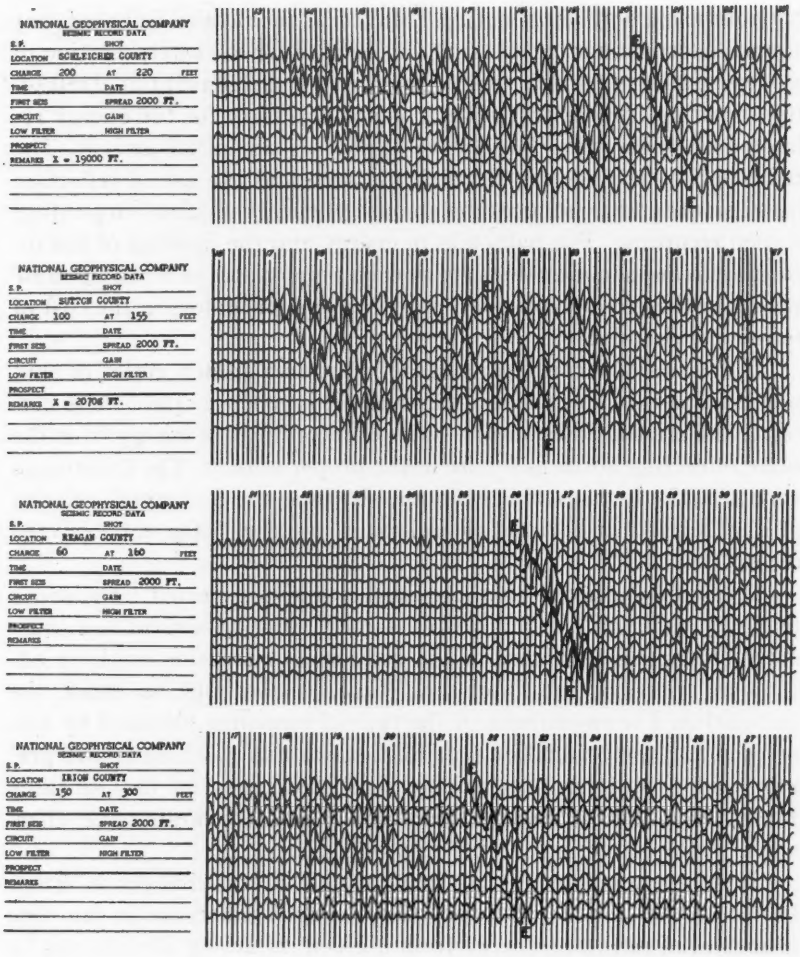


FIG. 3. Recordings of refracted events from different areas (note that each record is from a different county) showing similarity of character of refraction and of "step-out" times.

Since the inauguration of the Correlation Refraction Method several refinements have been made in interpretive technique; however, it is not considered advisable to disclose them at the present time.

The normal field procedure in a reconnaissance survey using the method is, first, to determine by refraction profiles and whatever well

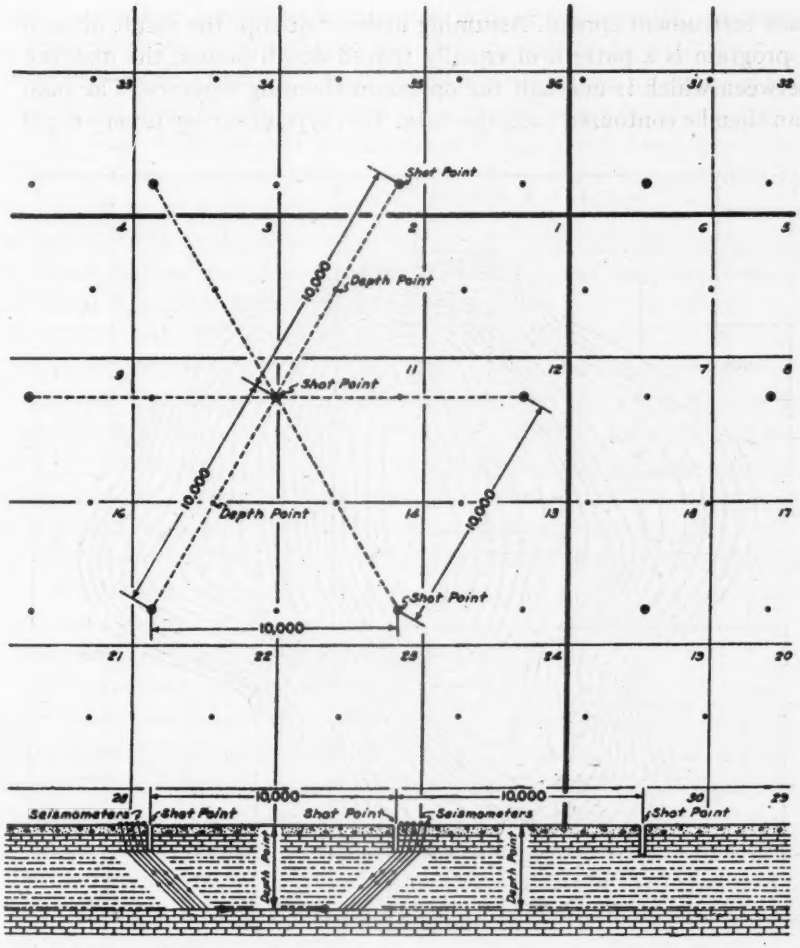


FIG. 4. Layout for refraction profiles.

data are available the proper horizontal and vertical velocities and the optimum shooting distance. Once the optimum distance has been determined, a hexagonal pattern of shot points is laid out using the optimum distance between points. (See Fig. 4.) "In-line" instrument spreads are laid out at each shot point and are shot from each of the six shot points at the vertices of the hexagon around the recording point. In this manner direct and reverse profiles are obtained at each point and "uphole times" for weathering corrections are available at

each instrument spread. Assuming little or no dip, the result of such a program is a pattern of equally spaced depth points, the distance between which is one-half the optimum shooting distance. The map can then be contoured to fit the data. This type of survey is very rapid

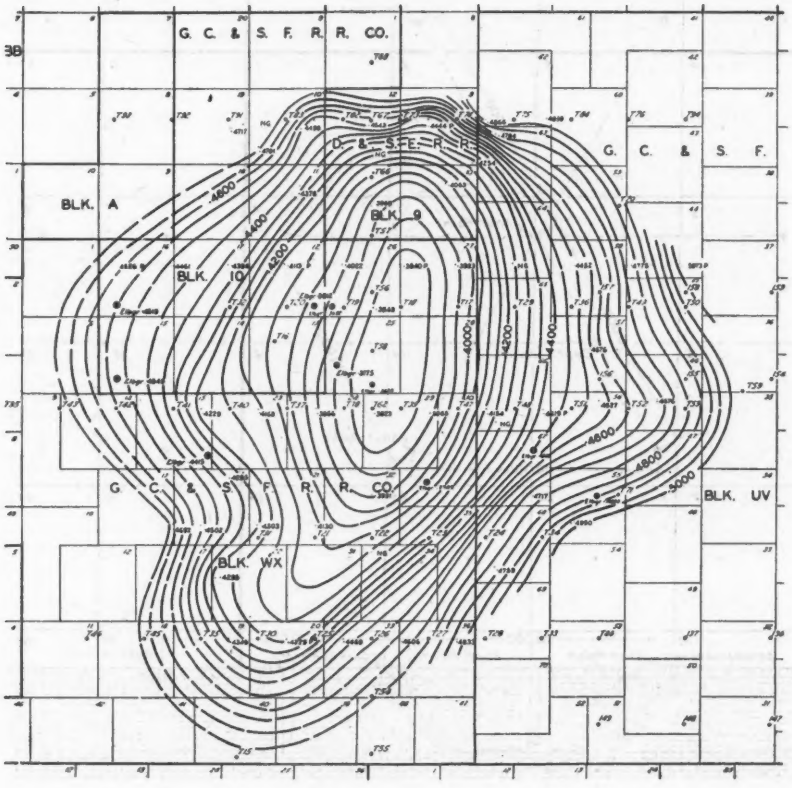


FIG. 5. Experimental refraction survey, Todd Area, Crockett County, Texas.

and economical but requires an area which is easily accessible. In areas which are inaccessible the hexagonal pattern has to be abandoned and lines or isolated spreads shot where possible. In the latter case, the cost of coverage is much greater for the same degree of control. In the case where isolated spreads are shot, every effort should be made to maintain a constant shooting distance. It must be realized that since the refracting horizon was assumed to be a plane between each shot point and instrument spread, the resolution of the method

has been reduced and small structures will not be revealed. Another point which must be treated cautiously is the fact that due to the long distances involved, small lateral changes in velocities will greatly influence the results and a continual check should be made on velocities.

An early experimental survey made in the Todd Area, Crockett County, Texas, has been selected to illustrate the type of results which can be obtained with the Correlation Refraction Method. This area is one in which to our knowledge it has been impossible to obtain reflections. The surface formation in the Todd Area is Lower Cretaceous Edwards limestone except in the valleys, where it is buried beneath the soil and fill. The optimum shooting distance selected in the area was 24,000 feet. It should be noted that the optimum shooting distance is not critical since the one distance served to interpret a horizon which varied in depth from 3,800 feet to 5,000 feet. Since this work was done on a known structure, no attempt was made to employ the reconnaissance shooting pattern. Detail lines were shot across the structure, shot points being 4,000 feet apart and employing 2,000 feet "in-line" spreads extending from 22,000 feet to 24,000 feet from the shot point. The shot holes were drilled to an average depth of 245 feet, and in most cases were not drilled through the lime into the underlying formations. The average charge used in the area was 130 pounds.

The results of the experimental survey (shown in Fig. 5) are based upon the correlation of refractions from a persistent refracting horizon either at or near the top of the Ellenburger limestone. On the top of the structure the event was recorded as an initial arrival; however, on the flanks where the Ellenburger is at a greater depth the event was recorded as a secondary arrival. Despite the fact that this was an experimental survey, done early in the development of the technique, a comparison will show reasonably close agreement between seismic results and available well data.

The authors wish to express their appreciation to The Atlantic Refining Company for their permission to use the experimental results in the Todd Area and to all of those who collaborated in the development of the technique.

REFRACTION EXPLORATION IN WEST TEXAS*

SIDON HARRIS AND GWENDOLYN PEABODY†

ABSTRACT

A brief historical summary of refraction shooting is given, followed by general comments on present "refraction correlation" methods applied to West Texas with special reference to the Edwards Plateau province.

INTRODUCTION

During the past three or four years the refraction method of seismograph exploration has been in a sense "revived" in certain portions of the United States. After being dormant for nearly a decade, this method can attribute its recent growth to the fact that it has been successfully used with modern innovations in areas where unsatisfactory results were obtained by reflection seismograph methods. A number of papers have been written describing the earlier refraction technique which began in old Mexico and the Gulf Coast region of the United States in the early 20's.[1,2,3,4,5] During this period, fan shooting was used extensively with considerable success in locating salt domes in the Gulf Coast region.

When refraction exploration was begun in West Texas during the later 20's, fan shooting was not found to be applicable since anticlines and folds were in general of low relief; thus it was difficult to detect a possible structure employing this technique. Refraction "profiling" was used by some operators in this territory with varying degrees of success, resulting in the discovery of several oil fields.

It can be seen easily that a number of disadvantages were related to the older type refraction methods. First, tremendous charges of explosives were required, frequently running as high as one ton per shot. Furthermore, the depth penetration was not very high in general as only first breaks were used. Also, an error in determining the dif-

* Read at the Dallas meeting of the Society, May 3, 1945.

† Southern Geophysical Co., Fort Worth, Texas.

[1] C. H. Dix, *Jour. Soc. Pet. Geophysicists*, Vol. VI, No. 1 (July 1935), pp. 34–43.

[2] D. C. Barton, Geophysical Prospecting for 1929, *A.I.M.M.E.*, p. 572, 1929.

[3] Sidon Harris, *Trans. Soc. Pet. Geophys.*, Vol. V, p. 121, 1934–1935.

[4] L. B. Slichter, *Physics*, Vol. III, p. 273, 1932.

[5] M. Muskat, *Physics*, Vol. IV, No. 1 (Jan. 1933), pp. 13–28.

ferences in velocities from the reversed time travel curves could seriously alter the magnitude of subsurface dips.

When the reflection technique began to develop in the late 20's, the refraction method was quickly abandoned in most areas. However, after some eight to ten years of successful reflection shooting in West Texas, certain areas were delineated as being unadaptable to the application of this technique because of interference produced by unfavorable surface conditions. In general, these areas of unsuccessful reflection results were ones covered by shallow deposits of hard limestone or caliche. The Midland Basin and Panhandle counties are spotted with these areas of more or less local significance. However, the vast area, commonly referred to as the Edwards Plateau, covering a number of West Texas counties, remains as the most fertile province for present and future refraction work.

MODERN WEST TEXAS REFRACTION TECHNIQUES

A few years ago several operators began experimental work in the Edwards Plateau area, and, more or less independently, developed what might be termed the "refraction correlation" technique. This new technique has several advantages over the old "first break layer to layer method." First, it is not necessary to obtain true first breaks, thus substantially smaller charges can be used. Second, it is not necessary to determine vertical velocities from refraction profiling alone. Third, computing procedures are greatly simplified and more uniform, thus reducing the limits of error. Fourth, due to the fact that higher order refractions are used, greater depth penetration can be obtained in certain areas with drastically reduced charges of dynamite. Improvement in instrument design has also undoubtedly been a great help in making the present refraction technique superior to the old methods used more than a decade ago in West Texas.

The success of modern refraction shooting is merely a question of tuning, involving the use of optimum shot point to recording distances and proper overall frequency response of instruments.

The computing procedures can be quite simplified. Fig. 1 illustrates one of the simple methods. Assume that a given refraction arrival observed on the record is coming from a bed with horizontal velocity V_2 and the average vertical velocity of the overlying sedimentation has a value V_1. In this case, the depth h_1, below weathering, of the high speed V_2 layer can be determined by the following:

$$h_1 = 1/2 \cdot \tan \alpha (T_2 V_2 - X_2), \qquad (1)$$

where sin α is V_1/V_2, T_2 is the arrival time of the particular refraction corrected to weathering, and X_2 is the shot point to seismometer distance measured on the surface. Weathering corrections for the shot point and seismometer can be handled as in reflection shooting. Usually the profiles are reversed and an average depth computed

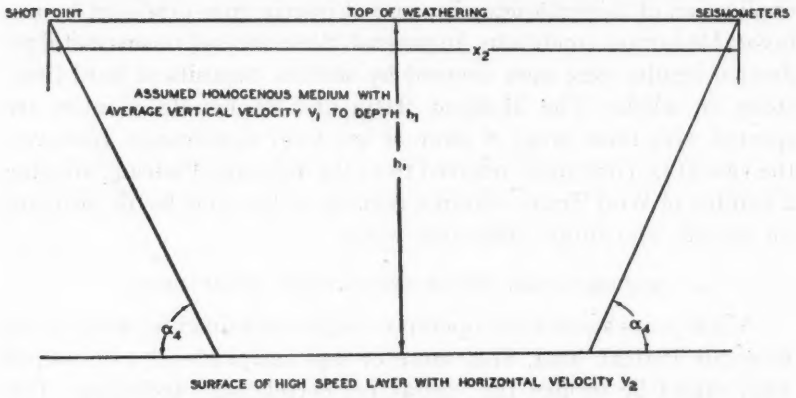


FIG. 1. Cross-section showing time travel path from shot point to surface of V_2 layer to seismometers.

and placed half way between shot point and seismometer. This method has proven successful in spot refraction correlation exploration in widely scattered areas of West Texas. Of course, certain refinements can be applied to this method by computing separate depths under each shot point if desired.

When starting exploration in a virgin province, the best procedure is to run a long, reversed refraction profile with distances varying from a few hundred feet to six or seven miles. Fig. 2 illustrates a typical reversed profile of this type obtained in certain parts of West Texas. This profile determines two factors in general. First, the optimum distance to employ in obtaining clean-cut refraction arrivals as close to the desired depth as possible; second, average horizontal velocities of the desired refracting horizons. For example, in Fig. 2 it can be assumed that a very desirable refraction arrival was obtained at a shot point to seismometer distance of 20,000 feet, at a corrected arrival time of 1.615 seconds. It appears that this particular arrival is coming from a horizon with a horizontal velocity of 19,200 feet per second when shot up dip, and 18,800 feet per second shot down dip. Thus it

reasonably can be assumed that the true horizontal velocity of the particular horizon is 19,000 feet per second. From consideration of available geological control and vertical velocity surveys in the area, let us suppose that we can expect an average vertical velocity of 13,000 feet per second to the depth of this particular refracting layer. Using 13,000 feet per second for V_1 and 19,000 feet per second for V_2, and substituting into equation (1), we obtain a value of .6848 for sin α;

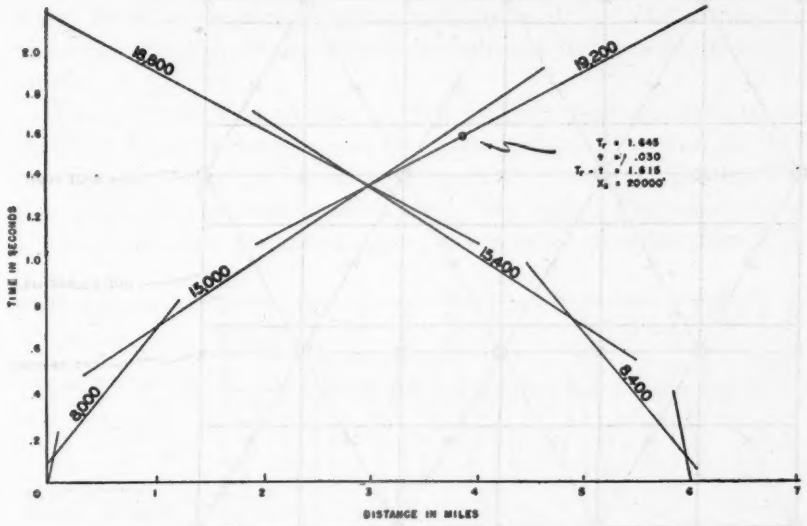


FIG. 2. Time travel curves for a six mile reversed refraction line.

therefore tan α equals .9398. Using a value of 20,000 for X_2, together with the above value for tan α, 19,000 for V_2 and 1.615 for T_2 in equation (1), we obtain a value of 5,000 feet for h_1, which is the depth below weathering for the particular refracting surface. If this depth varies appreciably from the anticipated one used in determining the average vertical velocity of 13,000 feet per second, the operation can be repeated, and by a process of successive trials, a value for V_1 can be derived that will fit with geological data and vertical velocity information in the area.

We are then ready to proceed with the regular reconnaissance correlation pattern. In this type of work, the value of h_1, determined in the above fashion, is averaged with a similar value obtained from a profile shot in the opposite direction. The average value is then subtracted from the average of the weathering plane elevations at the two shot

points involved, to obtain the sub-sea datum which is plotted on the map at this point. If more than one refraction is obtained, separate values for V_1 and V_2 have to be determined for each horizon mapped since the average vertical velocity to different depths varies, as well

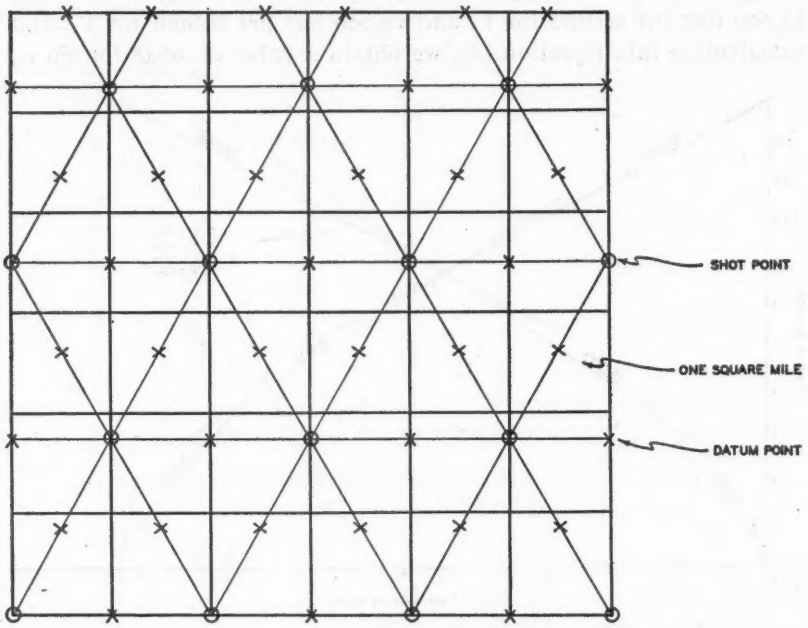


FIG. 3. A possible distribution of refraction shot points for spot correlation using two miles between shot point and recording station.

as the horizontal velocities along the tops of different refracting surfaces. However, it is rare if more than two refractions are obtained at the same shot point to seismometer distance. When the correct values of V_1 and V_2 have been determined for a particular prospect, a time depth chart can be prepared for each horizon, thus reducing the computing procedure to a very simple operation.

The computing methods discussed so far are highly simplified and we have assumed that average vertical velocities down to the refracting layer can be used in place of the separate layers of varying velocities which undoubtedly exist. We have also neglected any consideration of dips. Applications to the problem of a single dipping layer have been discussed in detail in a previous paper.[3] However, it would entail

accurately determining the horizontal velocities of the refracting horizon on both sides of the reversed profile. In general, it is not felt that the accuracy of the method to date justifies this refinement. After the first approximation has been made assuming a flat horizon, as described above, the data computed and contoured, a second approximation can be made employing the dip shown on the first approximation map, together with well known equations for a single inclined layer. Data for the second approximation are arrived at by using the angle of dip read from the original contour map between any two shot points.

Fig. 3 illustrates a possible pattern for refraction spot correlation shooting. Using twelve shot points per township, each hole can be shot six different ways, giving approximately thirty datum points. The shot point to seismometer distance is two miles. Frequently it is advisable to use a distance as great as six to seven miles. The same

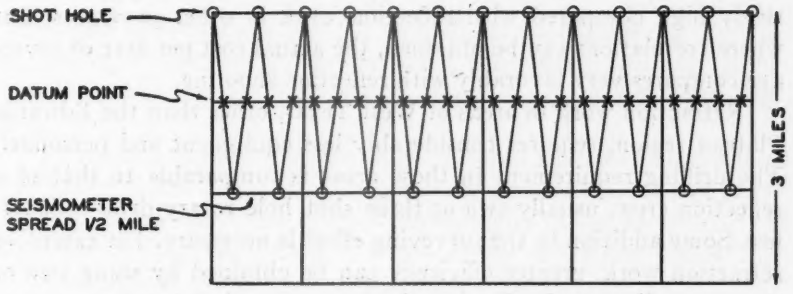


FIG. 4. A possible layout for a continuous refraction line.

inherent errors occur in correlation refraction work as in correlation reflection shooting, which involves the accuracy of the correlation to a given leg of the impulse.

Frequently it is desirable to shoot continuous refraction lines. Fig. 4 illustrates one method; two lines are laid out two miles apart and the shot points are as widely spaced along these lines as advisable to use in the particular area in a staggered fashion. Using the simplified method of computation described above, datum points can be obtained mid-way between the shot holes as indicated in the figure. Of course, other forms of continuous profiling can be used if desired. The selection of a particular pattern should depend largely on the characteristics of the area.

The accuracy of the method discussed so far varies considerably, depending upon the area, depth of penetration, and distances employed between shot point and seismometer. It is very important to obtain accurate horizontal distances, which makes the surveying problem a very important and essential phase of the work. Where definite correlations can be obtained or where continuous lines are used, anomalies with fifty feet of closure in the Permian zone or approximately one hundred feet of closure at pre-Permian levels can be detected with reasonable qualitative accuracy.

REMARKS ON FIELD OPERATIONS

Exploration in the Edwards Plateau region requires two or three surveying parties, six to eight spudder type drills, and two to four recording units. At times it is profitable to use two shooting trucks. Radio is used for communication and transmission of time breaks. A crew of this size requires forty to fifty men. The operating cost is relatively high compared with reflection work in other provinces, but where correlations can be obtained, the actual cost per acre of coverage compares very favorably with reflection shooting.

Refraction work in areas of West Texas, other than the Edwards Plateau region, requires considerably less equipment and personnel. The drilling requirement in these areas is comparable to that of a reflection crew, usually two or three shot hole rotary drills will suffice. Some addition to the surveying effort is necessary. For extensive refraction work, greater efficiency can be obtained by using two or three recording trucks. Frequently, however, only a small amount of refraction work is required to cover a local area where reflection shooting does not give satisfactory results. In this case, a reflection crew with multiple frequency response amplifiers can rapidly change to the refraction method with the addition of radio equipment.

CORRELATION OF REFRACTION SHOOTING*

G. A. GAMBURTSEV
(Condensed by L. W. Gardner)

The theme of this paper is that refraction seismograph investigations making use of techniques and equipment similar to those used for reflection operations can be carried out much more effectively than the older refraction technique of using only first arrivals. The paper is of interest not only because it furnishes a measure of the development of the art in Russia before the war, but also because it contains some thought provoking assertions. The original paper is long (twenty-two pages in original Russian, ten figures), since it contains a background of theoretical considerations, previous experience, and conceptions leading up to experiments and conclusions which are described, as well as discussion of the merits of the new developments in technique as compared with old technique. Essential features of the experiments, conclusions, and pertinent considerations are given below, without following the order or general arrangement of the original.

Experimental tests were begun in 1938 and a large volume of data was accumulated in 1940 in the area of Kovrov and Sudogda, Ivanov District, in the European Plain of USSR under the supervision of the Institute of Theoretical Geophysics, Academy of Science, USSR. This is an area where geological conditions are relatively simple.

* EDITOR'S NOTE: This rather unconventional publication of a condensation of a previously published paper has been made because the subject matter is closely related to that of the three preceding papers in this number, and because the difficulties of language and of securing the original are such that, otherwise, the material would remain unknown to most readers of GEOPHYSICS. Much of the material of a descriptive or general background nature is omitted in order to emphasize those parts which are new or of special interest to American exploration seismologists, and to show the progress of refraction exploration practice in U.S.S.R. before the war as indicated by this publication.

The condensation is based on the original paper as published in *Izvestiya Akademii Nauk SSSR. Seriya Geograficheskaya i Geofizicheskaya* (*Bull. Acad. Sci. U.R.S.S. Serie Geogr. et Geoph.*) *1942, pp. 26–47.*

Acknowledgement is made to E. D. Alcock of National Geophysical Company, who kindly sent a photostat of the original together with an English translation (by a professional translator) for use by the editor, and to Mr. Gardner who, at the editor's request, undertook the condensation as well as a certain amount of "interpretation" which was necessary to understand the translation.

These tests employed seismograph equipment consisting of electrodynamic detectors, amplifiers with filtering and amplitude regulating devices, and recording unit. The detectors were designed to have a natural period of 0.06 sec. with electromagnetic damping close to aperiodicity. Stable characteristics maintained equal for all detectors were emphasized. Filters had adjustable characteristics and could be set to pass low frequency oscillations. Sensitivity of the instruments was such that microseisms (or noise) limited further increase. The use of relatively low frequencies was dictated by the higher ratio of useful energy to noise for these frequencies. It was found that for long distance refraction waves (distance being measured from shot point to detectors), best results generally were obtained when events were recorded having periods of 0.03 to 0.05 sec. Interconnected detectors

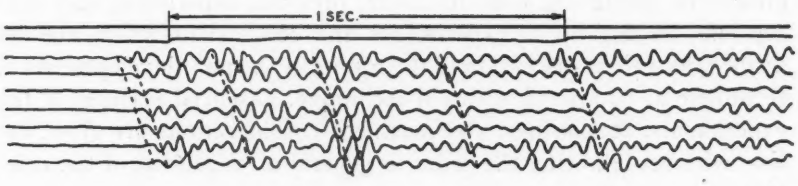


FIG. 1. Refraction record, vicinity of Kovrov, 1940. Recorded at distance of 32 km. with charge of 5 kg. ammonite [dynamite], using several detectors per trace with 100 meters distance between centers of groups.

were placed in groups [number of detectors per group not indicated] within an area [length] short in comparison with the apparent wave length (defined as $\lambda^* = V^*T$, where V^* is the apparent velocity and T is the period of the refraction wave), so that nearly vertical refraction waves would record additively. It was considered that microseisms (or noise) consist largely of horizontal waves, and the area [length] of distribution of the grouped detectors was large enough to cause interference between these horizontal waves. This grouping yielded a vertical vs. horizontal wave selectivity which improved the ratio of useful wave energy to noise energy. Detector groups were spaced 25 to 200 m. apart, and 100 m. spacing was subsequently recommended. Burial of detectors was considered as a possible method of further improving useful sensitivity, but was considered economically impractical for a large number of detector positions. All precautions were taken against avoidable noise disturbances, including placement of detectors away from ground surface irregularities.

The recommended procedure in shooting a profile is to shoot from each shot point toward a long line of detector positions beginning at the shot point and to repeat this operation for numerous shot points along the profile and for reversed directions of shooting.

The environment of the shot greatly influenced the seismogram obtained. Charges placed in holes up to ten meters deep or in water yielded best results and observations could be repeated satisfactorily.

Tests under these conditions yielded useful seismograms of refraction waves for distances as long as 30 to 37 kilometers with charges of ammonite [dynamite] of 20 to 40 kilograms. Figure 1 illustrates a

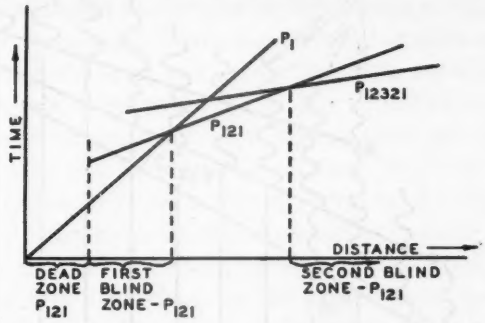


FIG. 2. "Dead" and "blind" zones for refraction from second layer (P_{121}). In "dead" zone, distance is too short for a refracted wave; in "blind" zone, refracted waves are not first arrivals.

record obtained under particularly favorable conditions at a distance of 32 kilometers with a charge of only 5 kilograms. Placement of charges at shallower depths (4 to 5 meters) required a slight increase in quantity of charge. In previous tests [presumably before redesigning equipment], it had been necessary to use a few hundred kilograms of explosive in order to record successfully at distances of 25 kilometers. Part of the improvement is attributed to better choice of shot point locations.

At distances of 2.5 to 3.5 kilometers, clear recordings were obtained with ammonite charges of 5 to 20 grams, when charges were placed in holes up to 10 meters deep or in water. When charges were placed in pits one meter deep, the quantity of ammonite had to be increased to one kilogram. When charges were placed in air, one meter above the ground, charges had to be increased to 5 kilograms.

Pertinent to the sensitivity of instruments, it was noted that in 1939 a sensitivity had been attained such that events recorded by the

reflection method were observed as late as a minute after detonation of the charge. These events appeared to be true reflections, and, if so, represented reflection surfaces at a depth of the order of 200 kilometers.

There is a "dead zone" for refraction waves near shot points within which no refraction wave energy exists for given refracting layers (Fig. 2). As distances are increased, waves following different

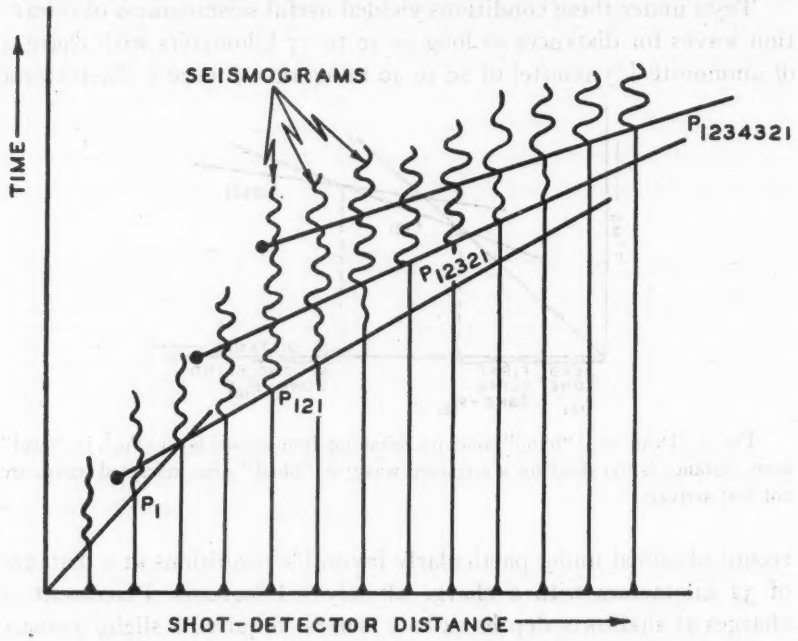


FIG. 3. Sequence of refraction seismograms illustrating correct correlations of events and possible miscorrelations in relying on first arrivals only.

refracting layers successively appear as first arrivals, and then are themselves overtaken by other waves. Except for their "dead zones," however, these waves exist and are recorded on seismograms as late events or first arrivals with amplitudes that diminish gradually with distances. The term "blind zones" has been applied to zones at distances from the shot point such that waves following a given refracting layer will not be observed as first arrivals.

The method of correlation by phases is advanced as a means of successfully making use of arrivals later than the first. According to this method, recordings deliberately are made sufficiently weak that

later events can be clearly recognized. It is stated that in the experiments, as a rule, a series of sharp "axes of synchronous phases" [correlative events] were recorded, which are parallel and inclined at different angles across seismograms. Figs. 1 and 3 illustrate this fact. These are similar in appearance to reflection events, except for their inclination. Individual groups of events are clearly recognizable and can be correlated by phases across seismograms, but the beginnings of events are difficult to identify. The use of later arrivals, in principle, eliminates the existence of "blind zones" and supplies useful information on refracting layers.

It is recognized that in correlating by phases a slight error in determination of apparent velocity may result due to absorption and dispersion affecting the form and period of events variably with distance. However, this is asserted to be of only minor practical importance since, in the final analysis, only a slightly incorrect value for the velocity of the refraction layer will be obtained, and true depths and dips will be determined. To minimize any error of this kind, it is important to record as nearly uniform frequencies as possible. Under this condition, experience indicated that readings of phases are more exact than readings of first deflections. In the experiments, occasional intense recordings were made which supplied information on the occurrence of first deflections for identification purposes and for making phase corrections, but usually this was not specifically needed and weaker recordings generally were made which permitted correlations by phases.

An experiment cited was one in which detectors were placed on a curved profile at a distance of 36 kilometers from the shot point. It was asserted that dependence on first arrivals would have led to false structural determination, whereas correlation by phases led to a correct representation. This type of shooting was done and is used mainly in areas where sharp underground relief is expected, and must be accompanied by radial profiles which help in deciphering the different types of waves.

From analysis of the records, it was found that, in general, waves must be longitudinal in character. No events were observed having velocities which could be attributed to waves which had transverse character while following the refraction layer. It was stated that these waves could not have transverse character at the ends of trajectories in low velocity material either. This follows energy considerations from which it was inferred that most of the wave energy gener-

ated at the shot would be of longitudinal character, that waves arriving at detectors would be nearly vertical so transverse components would not be recorded with vertical component detectors, and that an exchanged wave type at interfaces would not generally carry much energy, with one important exception. This exception is that within a high speed layer at a shallower depth than a given refraction layer, transverse wave energy may be relatively high. The occurrence of parallel events on seismograms is attributed to waves which are sometimes transverse and sometimes longitudinal within such layers. A useful consequence of this phenomenon is that if the upper layer has the higher speed, refraction waves following the lower refraction layer still will exist and can be observed. This is illustrated by Fig. 4.

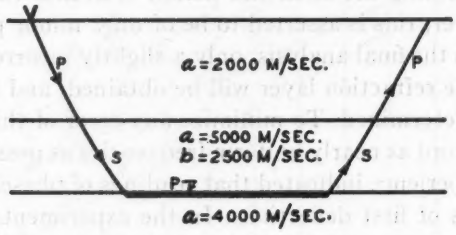


FIG. 4. Mixed type wave transmission. In medium 2, wave is transverse. In media 1 and 3, waves are longitudinal.

a = longitudinal wave velocity.
b = transverse wave velocity.

It is noted that if both longitudinal and transverse waves could be generated and recorded, substantial help would be obtained in resolving types of waves. However, present developments permit very useful determinations of depths and shapes of refraction layers. A very detailed differentiation of layers was possible. Velocity differences of 5 to 10% sufficed to locate them with certainty. In measuring velocity, it is necessary to distinguish between observed apparent velocity, which is influenced by the dip of the refracting layer, and true velocity.

Throughout the paper, attention is drawn to the similarity of this refraction method with usual reflection methods. A point of difference is that in correlating seismograms from different shot points, the simple continuous "chain" correlation which applies for reflection work does not apply for refraction work. However, there are over-all time relationships for refraction work which hold valid. The over-all time

for a given shot to detector must be the same if shot and detector positions are interchanged. Secondary relationships depend on this and the correlations across seismograms. Spacing of shot points in order to obtain effectively continuous and reverse control is a problem which is discussed as being related thereto.

In practice, it is necessary to analyze late events at optimum distances where different sets of refracting waves are separated and resolvable. The recommendation to shoot long continuous lines from shot points is made for the purpose of permitting more complete analyses of waves and to assure that data are available for optimum distances. There is also another purpose. It is to record reflections simultaneously, and thus furnish a means of interrelating reflection and refraction waves in a common system of time distance graphs.

It is pointed out that the refraction method furnishes no basis for determining vertical velocities; whereas, the reflection method does furnish such a basis. It is also noted that it is desirable to ascertain the shape of geological features by both methods as a double check. The reflection method is considered as an auxiliary to the refraction method.

In summary the method of correlation by phases suffices to yield useful results. By it, improper correlations of strong first arrivals can be avoided, and numerous refraction events later than the first can be used to great advantage. Similarity of technique to that used in reflection work is emphasized.

ON WELL VELOCITY DATA AND THEIR APPLICATION TO REFLECTION SHOOTING*

P. E. NARVARTE†

ABSTRACT

Current methods of computing seismic reflection data employing the integration of the actual velocity-depth (or velocity-time) relation in the velocity column are confronted with difficulties and limitations because they neglect the stratigraphic effect on the velocity distribution.

A method is proposed where the measured incremental time-depth relation, $\Delta Z/\Delta T$, to each of a number of stratigraphic markers may be combined into one generalized depth or time function satisfying well velocity data from a number of wells. The proposed method employs the integration of this slope relation and is used in conjunction with regional correction contour maps. Because this relation results from the combined load and stratigraphic effects together with the geological behavior of the section, this method offers distinct advantages both in accuracy and applicability. Advantages and limitations in the application of this method are discussed.

INTRODUCTION

Available velocity data lead to the conclusion that the two main factors determining the velocity of propagation of longitudinal elastic waves in the sedimentary section are overburden on the one hand and geologic age and composition on the other. Age and composition make up the stratigraphic factor.

While present overburden may not represent the full effect of loading on a stratum throughout its geologic past, the velocity through a given stratum displays a uniform relation with the depth of that bed. The effect of overburden alone on the velocity distribution in the section, exclusive of other factors, may be considered to be a continuous function,increasing with depth. The effect of overburden on the velocity through buried strata has been well illustrated in the past by Weatherby and Faust[1] and more recently by Haskell.[2] Whereas the overburden factor is uniform, it is by no means constant for all geologic ages; and while velocities increase progressively with age of the section traversed, the effect of depth on velocities shows a marked

* Presented at the fifteenth annual meeting, Tulsa, Oklahoma, April 4, 1945; and at the Houston and Dallas regional meetings April 20 and May 3, respectively, 1945.

† Petty Geophysical Engineering Co., San Antonio, Texas.

[1] B. B. Weatherby and L. Y. Faust, *Influence of geologic factors on longitudinal seismic velocities*. A.A.P.G., Vol. 19, No. 1 (Jan. 1935), pp. 1–8.

[2] N. A. Haskell, *The relation between depth, lithology, and seismic wave velocity in Tertiary sandstones and shales*. GEOPHYSICS, Vol. 6, No. 4 (Oct. 1941), pp. 318–326.

decline for the older beds to the extent that velocity in beds of Devonian age appears to be approaching an asymptotic value.

On the other hand, the stratigraphic effect on measured velocity columns, taken collectively, does not display a uniformity comparable to that of the load factor. The stratigraphic factor is composed of the effects of geologic age and lithologic composition. Of the two, the age factor only can be regarded as unidirectional (increasing with depth) for all practical purposes, but lacks uniformity in amount since the geologic unit, coincident with stratigraphic thickness, is quite variable. The geologic components of the section are present in widely varying thicknesses and frequently are entirely absent. This latter condition would result in a velocity contrast at the interface proportional in magnitude to the age contrast. The age component of the velocity gradient per unit of depth would be proportional to the geologic compactness, and the uniformity of this component would be comparable to the uniformity and completeness of the geologic column.

In comparing his data for California Tertiary with those of Weatherby and Faust for Gulf Coast Tertiary, Haskell[2] shows that the effect of overburden in his case is not appreciably different from that in the latter case. In order to achieve a comparison, the stratigraphic gradient of 0.104 over a 13,500 foot depth range in the former case was applied to the latter case covering only one-third the depth range, or 4,500 feet, through beds of comparable age. Hence, the stratigraphic correction applied to the case of the Gulf Coast was three times as great or 0.312 for the thinner section. Since the remaining load gradients were virtually the same, the converse relation can be postulated: that the stratigraphic gradients are inversely proportional to the depth range of distribution of a given age range.

The lithologic factor of the velocity column is quite erratic and conforms to no rule whatsoever. Its effect on the velocity column, unlike the other factors, is not unidirectional and may be so influential as to overshadow the combined effects of overburden and geologic age.

It is well to keep in mind that all three factors are present, each to a greater or lesser degree, in all velocity columns, and that any one may, in some cases, exert such influence as to be the dominant factor in shaping the velocity column. A few typical velocity columns taken from widely separated localities and covering a wide range of geologic age are given here to illustrate the combined effects of the factors governing the shapes of the velocity columns.

Figure 1 shows a typical Lower Gulf Coast velocity distribution taken from an accurate survey. This distribution exhibits some uniformity but not without certain irregularities resulting from change in composition. A rather typical zone of deceleration coincident with the shaley section at the base of the Miocene is quite apparent.

Figure 2 shows a typical velocity column through a slightly older section. This distribution is characterized by a sharp velocity con-

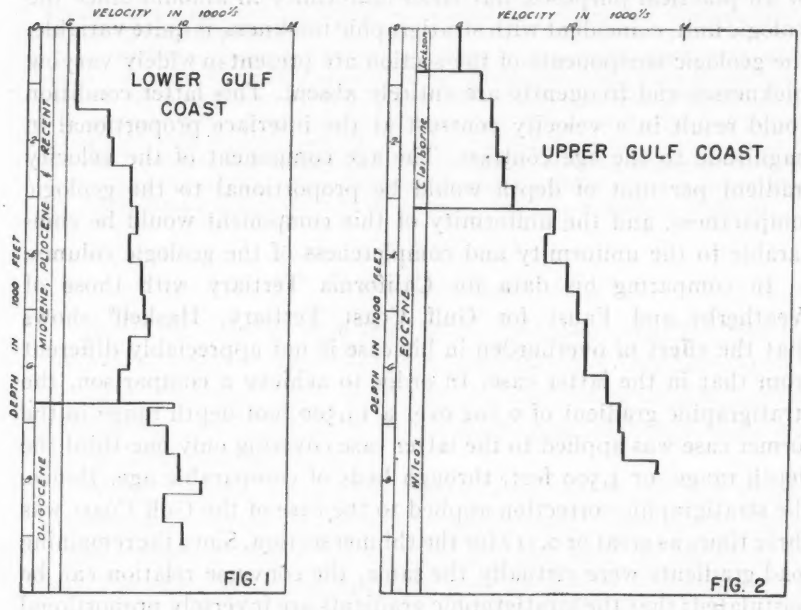


FIG. 1. Velocity distribution in Upper Tertiary section from an actual well survey in the Lower Gulf Coast.

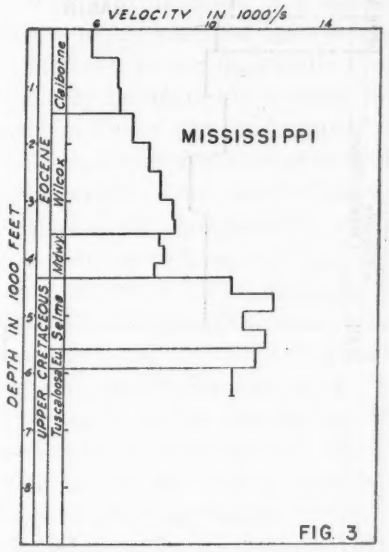
FIG. 2. Velocity distribution in Eocene section from an actual well survey in the Upper Gulf Coast.

trast at the Claiborne-Wilcox contact. The combined stratigraphic influence on this distribution is quite noticeable.

The older sections exhibit sharper contrasts. Figure 3 shows a velocity distribution, typical of certain parts of Mississippi, taken from actual measurements. This velocity column is characterized by a sharp velocity contrast between the Midway shale section and the underlying Selma chalk. Sharp velocity contrasts in this section are coincident with age and lithologic contrasts.

The velocity distribution of Fig. 4 is typical of certain parts of East Texas and shows a sharp contrast between the Upper and Lower Cretaceous. This distribution is no doubt influenced greatly by the combined stratigraphic factor, and sharp velocity contrasts are identical with stratigraphic contrasts.

Figs. 5 and 6 show typical distributions in still older sections. In Fig. 5 the thick Permian lime section of extremely high velocity is



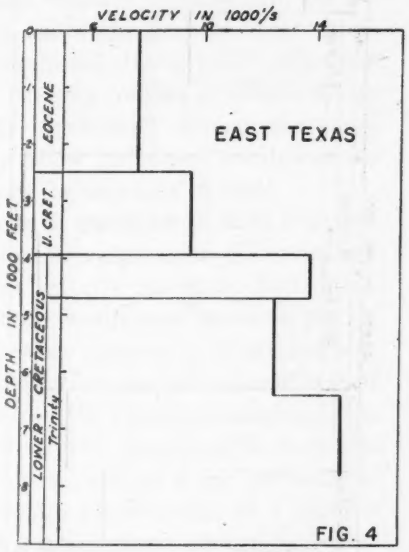


FIG. 3. Velocity distribution in Lower Eocene and Upper Cretaceous section from an actual well survey in Mississippi.
FIG. 4. Typical velocity distribution in Eocene and Upper and Lower Cretaceous section of East Texas from actual data.

underlain by older members of appreciably lower velocity. Fig. 6 shows extremely high velocity for a great thickness of Devonian shale section underlain by still faster limestone. The shale section is uniform in composition but exhibits no appreciable increase of velocity with depth. Obviously, the velocity distribution in both cases is governed largely by age and composition, overburden playing but a minor part.

It is therefore apparent that the influence of present overburden on the velocity column decreases materially with geologic age and that the stratigraphic factor is far more influential in shaping the veloc-

ity distribution in the older sections. It follows, therefore, that the planes of equal velocity in the section are more nearly horizontal in the younger section but follow the bedding plane more closely in older beds, in some cases, to the extent of virtual coincidence.

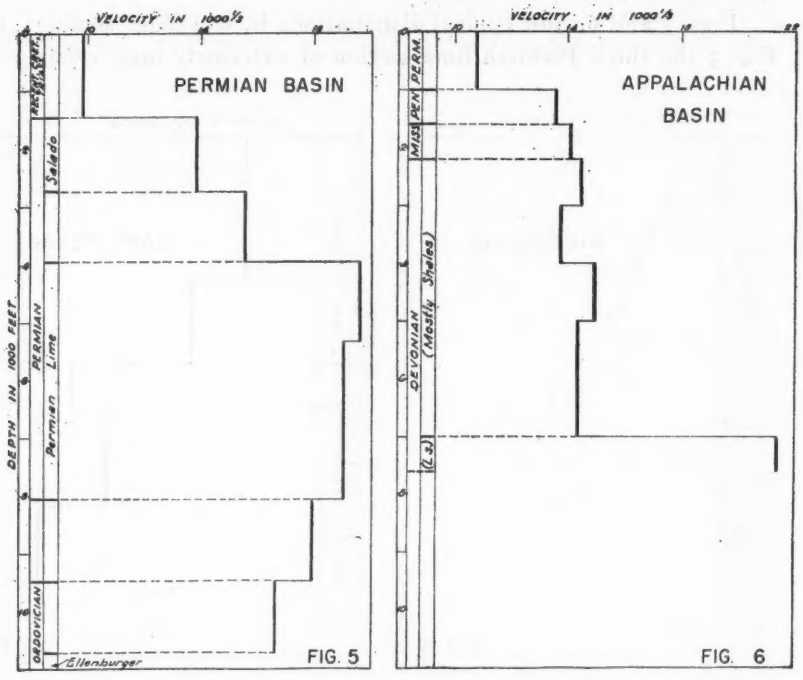


FIG. 5. Typical velocity distribution in Paleozoic section of the Central Basin Platform of West Texas from actual data.

FIG. 6. Typical velocity distribution in Paleozoic section of the Appalachian Basin from actual data.

THE USE OF REAL VELOCITY DISTRIBUTION

Well velocity survey data furnish the most accurate source of velocity information whereby to convert observed reflected time data into depth and dip. In order to achieve this conversion it has been common practice to fit smooth algebraic relations to the observed velocity data in order to represent the actual velocity distribution by a simple relation of convenient form suitable for a rigorous mathematical solution.

However, fitting a smooth relation with a reasonable degree of accuracy is confined to the relatively few cases that readily conform to the desired relation. As shown in the foregoing examples, those cases are probably the exception rather than the rule. This is not surprising since the velocity distribution in the section contains components that are not related to depth; and the significance and validity of such a generalization are conjectural to the degree that these components are influential.

The generalization of a measured velocity distribution, for instance, is not valid for extrapolation below the deepest observation. It has been shown that while the combined stratigraphic effect can be highly influential in shaping the velocity column it follows no set pattern. Hence the stratigraphic effect exhibited through the range of observations may change radically below the lowest point, and the extrapolation of the fitted relation may be seriously in error.

If a desired relation has been found to fit the observed data, it is common practice to integrate that relation into expression of curved ray paths and wave fronts, assuming that velocity planes are horizontal. While the mathematical solution for that condition is rigorous, the assumption is self contradictory since the very purpose of the method is to map dipping velocity interfaces. This solution disregards the effects of stratigraphy on the velocity column and the resulting inaccuracy in application is great to the degree that the stratigraphic factor is influential in the section. This is true as well of other methods of computation that employ actual velocity distribution, or a smooth relation to fit that distribution, in converting observed time to depth.

If the velocity distribution at a given point in an area is known either from direct measurements or from a reasonable estimate, it is generally assumed that that distribution will hold throughout an area, however small, immediately surrounding that point. This assumption, again, disregards the stratigraphic effect. If that effect is great, the use of that velocity distribution is usually confined within narrower margins, not because the assumption holds within those margins, but in order that the total error introduced between those margins will be reduced. In any case, an overall error is introduced that is proportional to the width of the segment where the relation is applied. In covering extensive regional areas of great relief, it becomes necessary to cut up the area into smaller segments and apply a different curve to each so as to distribute the over-all error that otherwise would be excessive.

In some cases, shot velocity data are available at more than one well within a segment where one common curve based on actual velocity distribution has been used. A final step in the interpretation of seismic data within that segment is to apply a correction from depth correction contours based on the amounts of misfit at each of the wells. Since this misfit frequently results from disregarding the stratigraphic influence, applying depth corrections in that manner could have the reverse effect of accentuating rather than diminishing the resulting error on structural relief.

It is to be expected, therefore, that the use of actual velocity distribution in computing reflection seismograph data is not without its serious drawbacks resulting from neglecting the stratigraphic influence on the velocity column. Because that factor is ever present and because of its capricious nature, attempts to rationalize the actual velocity distribution lead to difficulties commensurate with the importance of the stratigraphic factor.

THE SLOPE RELATION

It seems therefore that the actual velocity distribution at any one well is not alone sufficient to provide a satisfactory relation for computing seismic reflection data and that a more suitable relation would be desirable. Since the problem at hand is primarily that of determining the behavior of one or more reflecting planes from observed reflected times, a more suitable approach should be to consider the relation between time and depth to each of a number of horizons as those horizons vary in depth. A relation for each horizon can be determined either from well shot data, if available, or by direct comparison between reflected times to each horizon and logged depths at a suitable number of wells. Since it would be obviously disadvantageous to employ a different relation for each horizon, a means is proposed to combine a number of these relations into one.

Paradoxically, the very success of this method depends on the consistency of the stratigraphic effect on the velocity column. For, while exhibiting an erratic appearance, this effect has a definite stratigraphic position and significance, and stability of character as the section varies in depth. The success of seismic exploration itself rests on the identity of velocity discontinuities with stratigraphic interfaces.

Where suitable well shot velocity data are available, the desired relation can be determined as follows:

1. Select a suitable combination of well shot data from wells lying as nearly as possible along maximum regional dip to insure a maximum of subsurface relief with a minimum of lithologic change in the strata common to the wells. For the purpose of illustration, four velocity surveys have been selected lying in Mississippi and designated by Nos. 1 to 4 in Fig. 10. The time-depth relation for geologic horizons

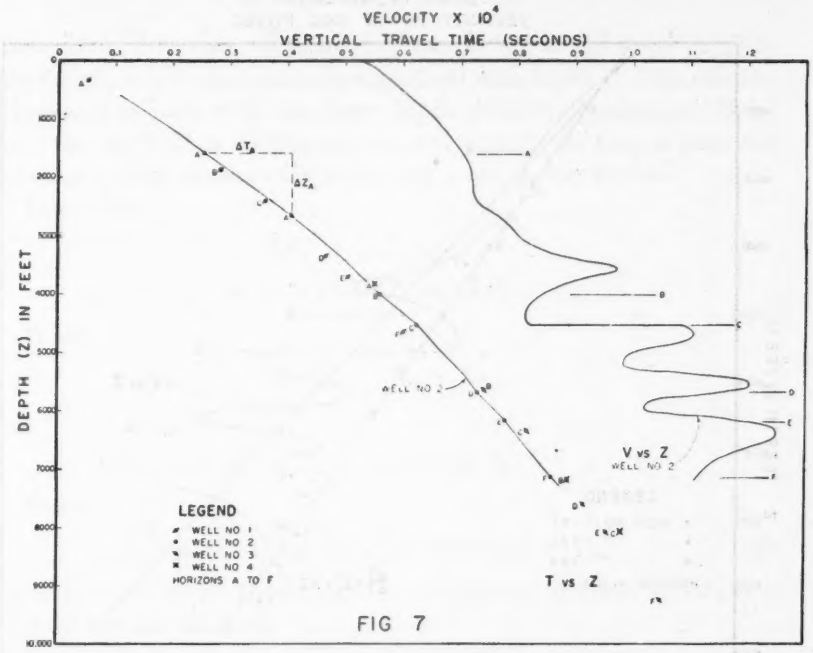


FIG. 7. Times plotted versus depth at each of four wells (Nos. 1 to 4) for horizons A to F and velocity distribution in well No. 2.

A to *F* at each of these wells together with the actual velocity distribution at well #2 are given in Fig. 7.

2. Determine the differential time-depth relation, $\Delta Z/\Delta T$, between each pair of adjacent wells for each horizon common to both wells, where ΔZ is the depth difference for one horizon between adjacent wells and ΔT is the corresponding time difference (see Fig. 7). For convenience we will refer to the relation $\Delta Z/\Delta T$ as slope.

3. Plot slope values against their corresponding mean depth as

shown in Fig. 8. This relation for each horizon should be smooth to the extent that the stratigraphic behavior above that horizon is uniform, and a smooth relation may be drawn for each horizon. By inspection, this relation, which will be referred to as slope-depth, for a number of horizons may fall close enough together to be combined into one common curve as in Fig. 8. Note the relative smoothness presented

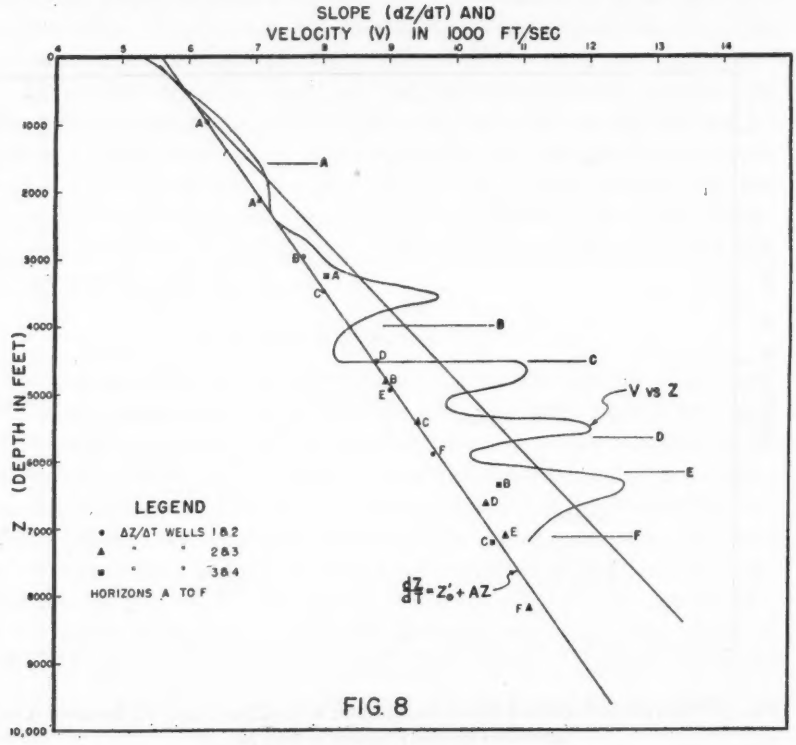


FIG. 8. Slope values (dZ/dT) for horizons A to F plotted against depth Z showing generalized slope-depth relation; and velocity distribution at well No. 2 showing generalized velocity-depth relation.

by the slope-depth relation as compared to the actual velocity distribution in well #2 given on the same plate. The difference in abscissae, representing the degree of stratigraphic effectiveness in the velocity column, denotes the error that would have been introduced by the use of the actual velocity distribution. It is significant that this difference increases with depth from a virtual coincidence at the sur-

face to a very considerable divergence with depth, and that the actual distribution diverges from the desired relation throughout virtually its entire length.

4. The resulting generalized slope-depth relation, if expressed in suitable form may be readily integrated into a time-depth function. In the case of a linear depth relation (Fig. 8),

$$dZ/dT = Z' = Z_0' + AZ \qquad (1)$$

where Z' is the slope value for any depth, Z_0' is the slope value at zero depth, A is the constant slope gradient with depth Z. This relation is identical in form with the linear depth velocity distribution. However, the slope Z' is distinguished from velocity in that it does *not* represent instantaneous velocity at any point in the section.

Integrating,

$$T = \int (Z_0' + AZ)^{-1} dZ$$
$$= (1/A) \log (Z_0' + AZ) + C.$$

When

$$Z = 0, \quad T = T_0$$

and

$$C = T_0 - (1/A) \log Z_0'.$$

Hence

$$T = (1/A) \log [(Z_0' + AZ)/Z_0'] + T_0, \qquad (2)$$

where T is the travel time to any given geologic horizon and T_0 is a constant for that horizon.

Solving for Z, equation (2) may be expressed in the form

$$Z = (Z_0'/A) (e^{A(T-T_0)} - 1). \qquad (3)$$

The time-depth relation of equation (3) intercepts the T axis at T_0. By substituting actual values from well shot data used in determining that relation the value of T_0 can be determined from equation (2) for each horizon at each well. Likewise, by plotting equation (3) on coordinate paper or making a suitable tabulation of depth for small increments of $(T-T_0)$, the value T_0 for each horizon at each well may be determined by comparing the actual travel times with values of $(T-T_0)$ for each corresponding actual depth as shown in Fig. 9.

Departures in the value of time correction, T_0, for one horizon from an average for that horizon may result from a misfit of the

generalized relation or from error in the original data. On the other hand, these divergences may have direct geologic significance since they may result from lithologic changes in the strata, either along regional dip or along regional strike. If the wells are not in good alignment, the velocity gradient along strike may be sufficiently great to be apparent in the correction contours to be contoured as explained later. If errors from this source are sufficiently great to affect the derived

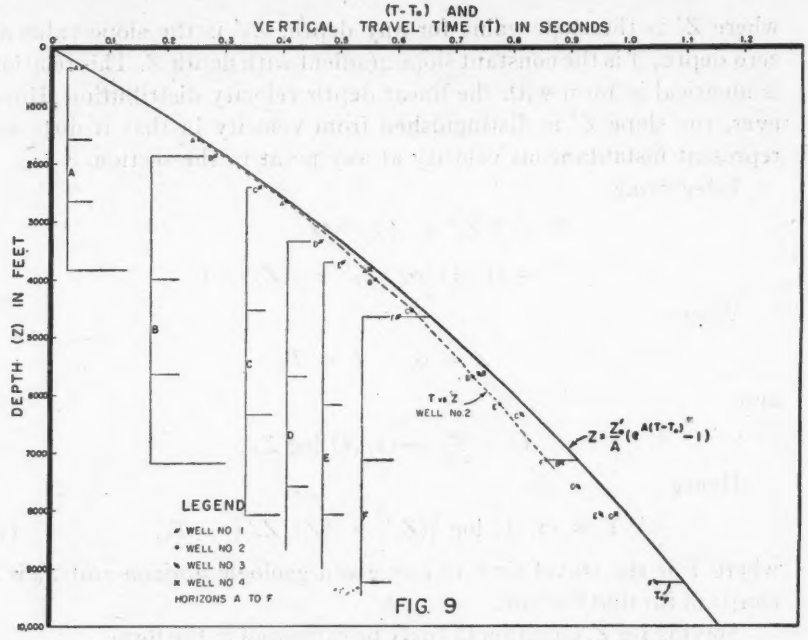


FIG. 9. Showing the relation between actual travel times to horizons A to F at well Nos. 1 to 4 and values of $(T\text{-}T_0)$ from integration of slope relation. Note that the difference in abscissae is virtually constant for any one horizon.

relation, adjustments may be made on the original data and a more accurate relation may be achieved.

After a suitable slope-depth relation has been determined that is applicable to a certain set of horizons, the value of T_0 is determined for each horizon at each well where measured times and depths to those horizons are available. These values may be posted on a map and a time correction contour map may be prepared for any one horizon. If conditions are favorable, the control wells for the derived rela-

tion should fall on correction contour strike, and the strike should be perpendicular to stratigraphic strike.

In Fig. 10 are shown time correction contours for horizon *C* in the area under consideration using the slope relation. Being relatively free of the influence of regional dip, these contours are practically normal to regional strike at the control wells. In contrast, Fig. 10-A shows correction contours for the same horizon using the actual velocity

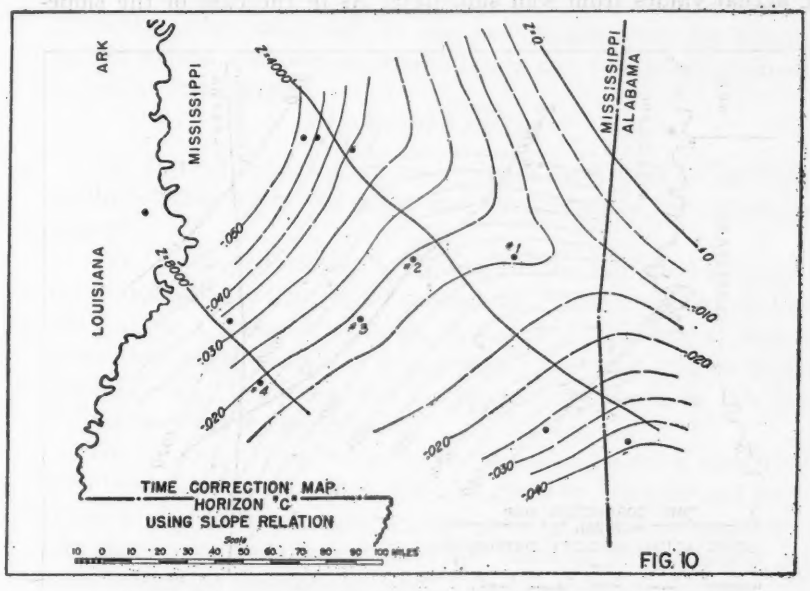


FIG. 10. Time correction map showing values of T_0 for horizon *C* using the slope relation. Note that correction strike is virtually perpendicular at the control wells to regional strike of horizon *C* given by depth contours at 0, 4000, and 8000 feet.

distribution at well #2. The contours in this instance, being strongly influenced by regional dip, are parallel to regional strike at the control wells.

A similar procedure may be followed in the case when a slope relation with time is desired. For a linear slope-time relation,

$$dZ/dT = Z' = Z_0' + KT \qquad (4)$$

where K is the constant slope gradient with time T, and Z_0' is the value of Z' for $T=0$.

By integration,

$$Z = Z_0'T + \tfrac{1}{2}KT^2 + Z_0 \qquad (5)$$

where Z_0 is the value of Z for $T=0$.

The time depth relations for the various horizons will be a family of curves having a Z intercept of Z_0 determined individually for each horizon.

The value of Z_0 for a given horizon may be obtained by substituting actual values from well shot data. As in the case of the slope-

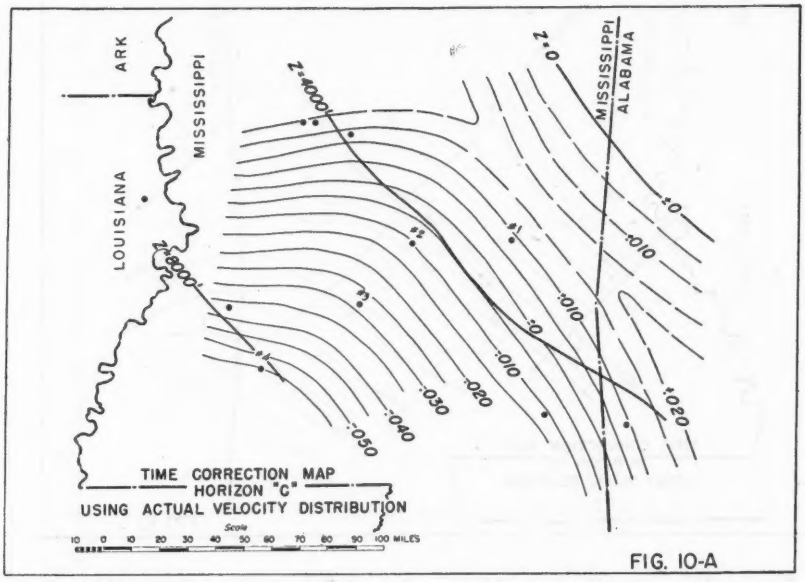


FIG. 10-A. Time corrections to horizon *C* from comparison of actual travel times with actual time-depth data of well No. 2. Note that correction contours parallel regional depth contours at the control wells showing influence of dip.

depth relation, these values may be treated separately at each well. Upon application of all available velocity data to the above relation for a given horizon, depth correction values may be determined for that horizon at each well and correction contours may be drawn. Depth correction maps have the same significance and application as time correction maps for a slope-depth relation.

The time-depth relation obtained by integrating slope-depth or slope-time relations is based on the pattern governing the stratigraphic

distribution at the control wells. It is accurate in application to intermediate areas to the extent that this pattern remains uniform in those areas. It follows that the correction contours are responsive to sharp changes in the stratigraphic distribution not only resulting from faulting[3] but from pinchout or truncation of strata of abnormal velocity as well, or from any abnormal behavior of the section traversed. Hence a knowledge of regional subsurface behaviour based on well log data may be used to good advantage in shaping correction contours. The correction maps may well be enriched progressively by tying into drilled wells in the process of exploration and determining correction values at those wells.

CURVED PATHS

The derived slope relation readily lends itself by direct application to the solution for curved paths and wave fronts in the conventional manner.

The time-depth relation to a given horizon exhibited by equation (3) is analogous to that for a hypothetical section overlying that horizon having a linear velocity-depth distribution identical with the generalized slope relation of equation (1), the travel time to depth Z being $(T-T_0)$. It follows that the iso-velocity planes in this hypothetical medium are horizontal.

The solution for curved paths and wave fronts for a velocity distribution of this familiar form has been given by Slotnick[4] and may be found in recent texts on geophysical prospecting.[5] A similar solution may be determined as well for slope relations that conform with other integrable functions of depth.

It might be stated briefly that a similar procedure may be followed for slope-time relations. In that case, however, the correction constant identified with a given horizon would be a depth correction.

GENERAL APPLICATION

While the method given here for determining the slope relation is adaptable to cases where suitable velocity data are available, the use of the slope relation should by no means be confined to those cases. Given the velocity distribution at one well, the geological be-

[3] E. J. Stulken, *Seismic velocities in the Southeastern San Joaquin Valley of California*, GEOPHYSICS VI, No. 4 (Oct. 1941), p. 336.

[4] M. M. Slotnick, *On Seismic Computations with Applications*, GEOPHYSICS I, No. 3 (Oct. 1936), pp. 299–302.

[5] Such as Nettleton: *Geophysical Prospecting for Oil*, 1940, p. 257.

havior of the section (i.e., the relation of the dip of the bedding planes to depth), and a reasonably accurate value of the load factor for each significant component of the section, a slope relation can be determined synthetically. While some error may be introduced in this synthesis by inaccuracy in any of its component relations, the advantage gained by the use of that relation should more than offset that error.

CONCLUSION

A method has been proposed for the complete solution of seismic reflection data employing the integration of a slope relation with depth, or time, exhibited by observed data. Because this method is based on actual relations, it takes full account of the combined effect of the overburden and stratigraphic factors in conjunction with the geologic behavior, all of which govern those relations. The proposed method, used in conjunction with correction maps, offers distinct advantages in regard to both accuracy and application.

Because the fundamental slope relation employed satisfies a geologic pattern as exhibited by well shot data employed in its determination, this method is applicable in areas adjoining the control wells to the extent that the pattern exhibited by the control wells remains unaltered in those areas. This is particularly significant in mapping structure where the normal stratigraphic pattern may be altered materially. An appreciable error in the mapped relief may result from abnormal thinning, pinchout or truncation, of abnormally high or low velocity beds above the horizon mapped. If the error from this source is significant, special depth or time corrections adapted to existing conditions may be applied locally. It is well to point out that this source of error is not peculiar to the slope relation but is common as well to all other methods employing a predetermined generalized relation.

Some of the advantages offered by the use of the derived slope relation in conjunction with correction contours are briefly outlined here.

1. One properly constructed relation may be applicable over wide areas.

2. The use of that relation portrays dip more accurately at well control points and elsewhere within its area of application.

3. The method is mathematically rigorous and conforms with existing conditions.

4. The method is simple in derivation and application. Fitting a smooth function to slope-depth or slope-time data is not critical and does not justify painstaking methods. A good visual fit should be considered satisfactory. The effect of a slight misfit will generally be absorbed in the correction gradient.

5. The relation is accurate for extrapolation down-dip below the lowest observed data for each horizon to the extent that the geologic pattern governing that relation holds for greater depths of those horizons.

6. Since the correction contours resulting from comparing this relation and actual data are relatively free of the influence of dip, the correction gradient is at a practical minimum permitting more accurate areal interpolation between control points as well as extrapolation beyond the control depth range.

7. Correction contours afford an excellent analysis of regional velocity variation resulting from lithologic and stratigraphic changes.

Other advantages may be found upon application.

While this method is not intended to solve all conditions likely to be encountered in reflection prospecting, it may be used to advantage in the large majority of cases, wherever the stratigraphic pattern permits the use of a continuous generalized relation. The method has been used extensively by the writer over a wide range of geologic age and has been found decidedly advantageous.

The writer wishes to express his thanks to the Petty Geophysical Engineering Company for permission to publish this paper.

AIRPLANE NOISE INTERFERENCE WITH SEISMIC PROSPECTING*

J. M. KENDALL†

ABSTRACT

The low frequency sound produced by airplanes is briefly investigated, and its propagation through the atmosphere is considered. Data on a cargo type airplane are presented. Rough calculations to determine the response of geophones to this sound field indicate that one airplane can blanket an area of several hundred square miles. Measures suggested for minimizing the interference are discussed.

INTRODUCTION

The great amount of present day aircraft activity with its associated noise is presenting a minor problem to geophysical crews using the seismic reflection instruments. These instruments are especially vulnerable to aircraft noise because of the fact that the spectrum of his noise lies squarely in the middle of the instrument frequency response characteristic. Moreover, the airplane is probably the most powerful man-made generator of low frequency acoustic waves known. On account of its high altitude vantage point, one large military plane appears to be quite capable of causing seismic interference over a radius of about eight miles.

AIRPLANE SOUND AND ITS PROPAGATION

Before proceeding with the consideration of the interference with seismic prospecting, we shall investigate the characteristics of airplane noise and the propagation of sound waves through the atmosphere. Most of the sound produced by airplanes comes from the rotating propellers and is of the fundamental frequency.[1,2] Moreover, this fundamental frequency is almost always within the range of 45 to 90 c.p.s. According to theoretical calculations,[1] a rotating propeller radiates the sound pressure of the fundamental frequency out more or less in a conical shell 120° back from the forward direction. However, in an actual measurement made by the writer, the results of which are shown in Fig. 1, the radiated sound pressure appears, in this case, to lie principally in the plane of rotation of the propeller.

* Read at the Tulsa and Houston meetings of the Society, April 1945.

† The Naval Ordnance Laboratory, Washington, D. C.

[1] N.A.C.A.T.R. 526 (1936).

[2] The exhaust noise is usually much lower than the propeller noise.

These data were taken on a U. S. two-engine cargo type airplane flying at approximately 250 m.p.h. By the procedure described later herein, due allowance was made in this curve for the advance of the airplane through the air (at roughly one-third the velocity of sound).

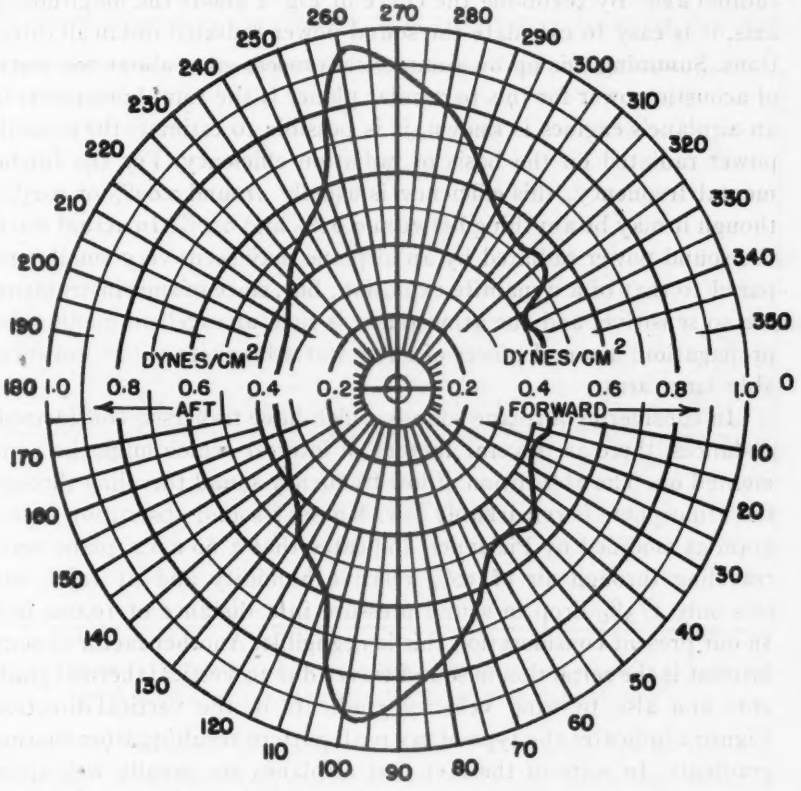


FIG. 1. Directional sound radiation characteristic of a two-engine cargo type airplane. The sound pressure in dynes per square centimeter is for a distance of 10,000 feet from the airplane.

In other words, distortion of the sound field caused by the high velocity of the airplane compared to the sonic velocity has been taken out. The curve therefore represents the directional radiation characteristics of the airplane when the airplane is considered to be motionless but producing all of the sound produced in normal flight. The curve gives the sound pressure in dynes/cm^2 as a function of angle around the airplane in the horizontal plane at a distance of 10,000 feet. It is be-

lieved to be a safe assumption that very nearly the same curve would have been found for the vertical or any other plane containing the longitudinal axis of the airplane. The directional radiation characteristic is therefore assumed to be symmetrical about the airplane's longitudinal axis. By revolving the curve of Fig. 1 about the longitudinal axis, it is easy to calculate the sound power radiated out in all directions. Summing this up by a numerical process gives about 200 watts of acoustic power for this particular plane. If the total horsepower of an airplane's engines is known, it is possible to estimate the acoustic power radiated on the basis of radiation efficiency. For the fundamental frequency, this efficiency is usually around 0.02% or 0.03%, though it may be anything between 0.01% and 0.1%. In actual watts the sound power radiated by an airplane may seem very small compared to that of a dynamite explosion; but, since seismic instruments are so sensitive, and the atmosphere is such an excellent medium for propagation, a sound power of a few watts blankets out an unbelievably large area.

In considering airplane sounds which have traversed considerable distances, there are several factors of interest which might be commented on. The absorption of low frequency sound traveling through the atmosphere is remarkably low. Kneser's sound absorption nomogram as modified by Pielemier[3] indicates that a 60 c.p.s. plane wave traveling through air of 50% relative humidity and at 20°C, suffers only 1/3% drop in sound pressure in a distance of 10,000 feet. In our present consideration this is negligible. Another factor of some interest is the refraction of sound waves due to vertical thermal gradients and also to wind velocity gradients in the vertical direction. Figure 2 indicates the type of ray path pattern resulting from thermal gradients. In spite of the fact that airplanes are usually well above the earth's surface, the refractive effects will become appreciable at a point on the earth's surface several miles away. The refractive effect of thermal gradients has been calculated by Haurwitz,[4] who finds that when the temperature decreases 6°C. for each km rise,[5] an airplane

[3] W. H. Pielemier, *J.A.S.A.*, 16, 273 (1945).

[4] B. Haurwitz, *Jour. of the Aeronautical Sciences*, Vol. 9 N2 (Dec. 1941).

[5] Prandtl, in *The Physics of Solids and Fluids* (Blackie & Son), Part II, p. 169, states that the minimum requirement for a stable atmosphere free from thermal convection currents is that the atmosphere have horizontal "adiabatic stratification." This occurs when the temperature falls by 1°C. for a rise of about 100 meters. A lesser gradient results in increased stability.

at 3 km (10,000 feet) altitude will not be audible at distances greater than 23.6 km (about 14 miles). Practically, as shown later herein, this range of audibility is great enough that it imposes no effective limit as far as seismic prospecting is concerned. The effect of wind velocity gradients (increase of velocity with increase of height) cannot be predicted on account of the great variability of winds. However, it would

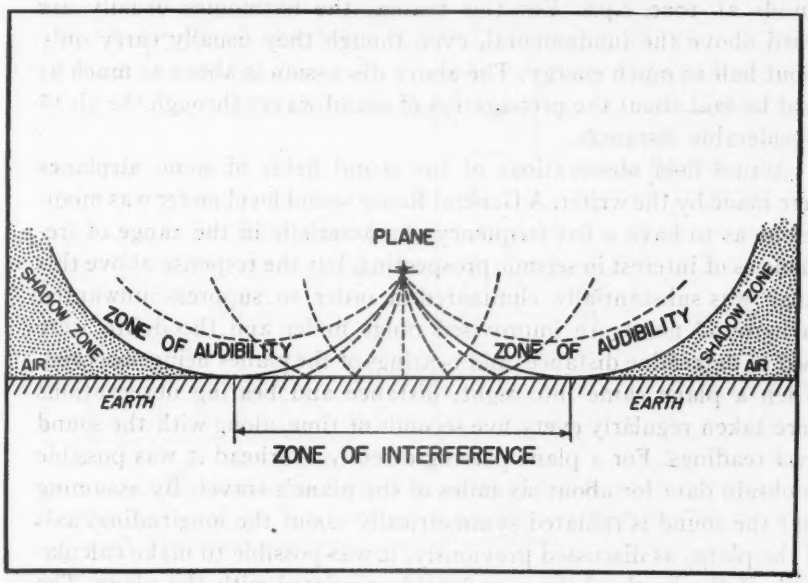


FIG. 2. The "acoustic bowl" due to temperature decrease with altitude. Interference with seismic work may be expected in the zone of interference.

appear that the effect can easily be greater than that due to thermal gradients.[6] A fundamental difference between the two is that thermal gradients are effective symmetrically, while wind gradients favor reception of the sound waves downwind and hinder them upwind.

In addition to absorption and refraction, it is, of course, necessary to take into account the inverse first power law for decrease of sound

[6] This would be unusual, however. Curves showing wind velocity as a function of altitude averaged over several years are given on page 135 in W. J. Humphreys' book, *Physics of the Air*, 3rd ed., 1940 (McGraw-Hill). These curves indicate that the wind velocity is seldom over 10 meters/sec. (33 feet/sec.) greater at 3 km (10,000 feet) than it is at the surface. A simple calculation based on these data indicates that the audible zone on the ground should extend about 19 miles upwind from the point directly beneath the airplane.

pressure with distance. Furthermore, it must be remembered that, when sound waves are reflected from an unyielding surface, the pressure on the surface is doubled. Another incidental comment that might be made at this point is that, in making measurements, there is evident difficulty in judging airplane noise intensity by ear. The ear is about 200 times less responsive to sounds at 60 c.p.s. than it is to sounds at 1000 c.p.s. For this reason, the harmonics usually are heard above the fundamental, even though they usually carry only about half as much energy. The above discussion is about as much as need be said about the propagation of sound waves through the air to considerable distances.

Actual field observations of the sound fields of some airplanes were made by the writer. A General Radio sound level meter was modified so as to have a flat frequency characteristic in the range of frequencies of interest in seismic prospecting, but the response above this range was substantially eliminated in order to suppress unwanted background noise. An improvised range finder and theodolite were used to determine distances and bearings of the planes being observed. When a plane came into sight, distance and bearing observations were taken regularly every five seconds of time, along with the sound level readings. For a plane passing directly overhead it was possible to obtain data for about six miles of the plane's travel. By assuming that the sound is radiated symmetrically about the longitudinal axis of the plane, as discussed previously, it was possible to make calculations of the levels of the sound field associated with the plane. The symmetry is not spherical, since the plane radiates more sound energy to the sides and up and down than it does in either the forward or aft directions. Fig. 3 shows a contour map of the sound pressure associated with a two-engine cargo type airplane flying at an altitude of 10,000 feet at 250 m.p.h. This airplane is more or less typical of the sort which might be observed. The map was prepared from calculations based on the data contained in Fig. 1. In making the calculations for Fig. 3, allowance was made for the inverse first power law of decrease of sound pressure with distance and for pressure doubling at the earth's surface, but not for atmospheric absorption, which is negligible, and not for wind velocity gradients, nor for thermal gradients.

The plot shows contours for pressure levels of 0.05, 0.1, 0.2,0.5 and 1.0 dynes/cm^2. The cross section lines represent section lines, 1 mile apart. It is to be noted that the contours are somewhat crowded

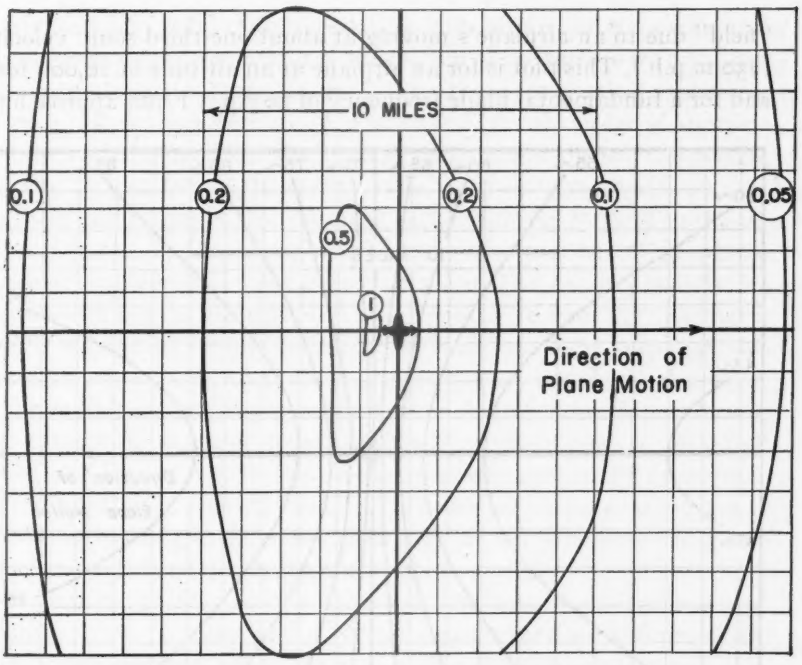


FIG. 3. Sound pressure contours on the earth's surface for a two-engine cargo type airplane. Altitude 10,000 feet, speed 250 m.p.h. The coordinate lines are spaced one mile apart. The contours represent dynes/cm² as marked.

ahead of the airplane, which circumstance is probably due to the airplane's traveling with a speed equal to about 30% the velocity of sound in air. On approaching, the sound levels recorded at the observation point simultaneously with the visually measured distances were produced by energy previously radiated by the plane when it was 30% farther away than it was at the time of the visual observation. After the plane had passed over and was receding, the reverse condition was true, thus causing a higher sound level because the energy causing the sound measured was radiated by the airplane when it was 30% closer to the observer than indicated by the simultaneous visual observation. The great lateral extent of the contours is attributed to the directional radiating characteristic of the airplane.

The Doppler effect resulting from a sound source moving as rapidly as an airplane does is of interest in connection with seismic prospecting. Fig. 4 was prepared to give a graphic idea of the frequency

"field" due to an airplane's moving at about one-third sonic velocity (250 m.p.h.). This plot is for an airplane at an altitude of 10,000 feet, and for a fundamental blade frequency of 60 c.p.s. From approaching

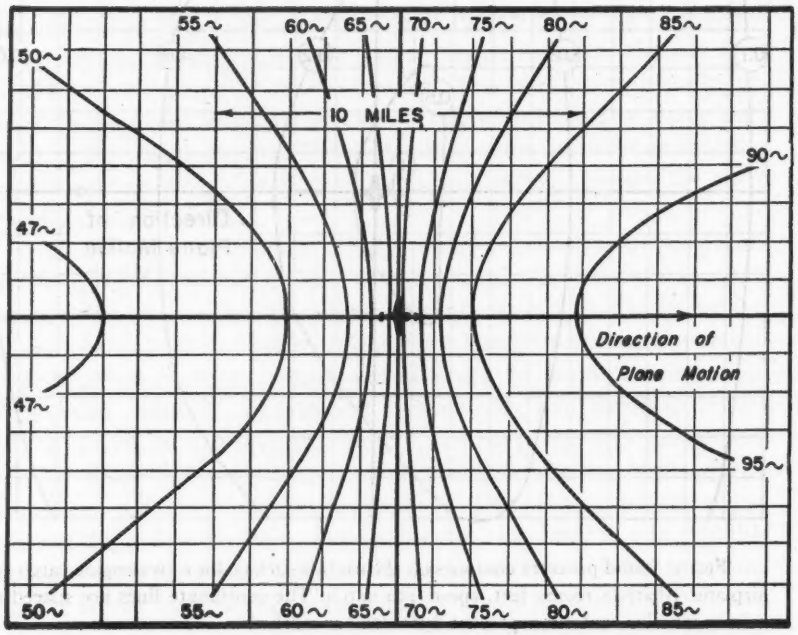


FIG. 4. Frequency contours on surface of earth due to an airplane moving at approximately one-third sonic velocity. Altitude 10,000 feet, speed of airplane 250 m.p.h., fundamental blade frequency 60 c.p.s. The coordinate lines are spaced one mile apart.

to receding, the frequency decreases a full octave in the case of an airplane passing directly overhead. The true frequency of 60 c.p.s. occurs after the plane has passed over by an amount equal to about one-third of its altitude.

RESPONSE OF GEOPHONES TO AIRPLANE NOISE

The above discussion concerns the airplane as a rapidly moving sound source and the sound pressure it produces at the surfaces of the earth. We shall now consider the interference with seismic prospecting due to these sounds.

When sound waves in the air are reflected from the earth's surface the resulting pressure produces motion in the earth. Even with oblique

incidence when total reflection occurs, the surface of the earth still has motion. Since calculations of the motion of the surface with oblique incidence are much more involved than those for vertical incidence, no such calculations were made, nor required for the order of approximation needed here. The velocity of propagation of the soil comprising the first inch or two of the earth's surface varies from 175 ft./sec. for very soft soil to 750 ft./sec. for hard dirt, according to Wolf's calculations[7] based on Washburn and Wiley's measurement of geophone response[8] as affected by the geophone plant. The velocity rapidly increases with depth, however; for, at a depth of 10 feet, the velocity is usually something around 2000 ft./sec. Based on these velocities, the sound pressure at 60 c.p.s. necessary to give an amplitude of motion of the earth's surface equal to the ground unrest of 10^{-8} cms usually encountered in a quiet location[9] has been calculated to be 0.041 dynes/cm^2 for the 175 ft./sec. surface velocity and 0.127 dynes/cm^2 for the 750 ft./sec. surface velocity.[10] The lowest values of sound pressure for producing interference then may be set somewhere between 0.05 dynes/cm^2 and 0.2 dynes/cm^2.

Returning to Fig. 3, it is seen that the 0.05 dynes/cm^2 contour extends about 10 miles ahead of the airplane and an estimated 15 miles to the rear and sides. The area within this contour is something like 750 square miles. The corresponding area for the 0.2 dynes/cm^2 contour is only about 75 square miles. The area of the interference

[7] Wolf, A., GEOPHYSICS, Vol. VII, No. 2, p. 119 (1942).

[8] Washburn and Wiley, GEOPHYSICS, Vol. VI, No. 2, p. 122 (1941).

[9] Wolf, A., GEOPHYSICS, Vol. IX, No. 1, p. 34 (1944).

[10] These values of sound pressure required to give earth motion equal to ground unrest were arrived at with the aid of the following formula derived by Dr. A. Wolf of the Geophysical Research Corporation, Tulsa, Oklahoma:

$$\frac{\rho v \dot{u}}{P} = \frac{-\frac{1}{2} + \xi \coth(\xi \log k) + j\sigma}{\frac{1}{2} + \xi \coth(\xi \log k) + j\sigma}$$

where

$$\sigma = \frac{\omega a}{(k-1)v} \quad \text{and} \quad \xi = (\tfrac{1}{4} - \sigma^2)^{1/2}$$

$\dot{u}$ = vector particle velocity of the earth's surface.
v = velocity of propagation in the material of the earth's surface.
ρ = density of the material of the earth's surface.
$\omega = 2\pi$ times frequency in c.p.s.
a = depth at which the velocity of propagation has increased to kv.
k = ratio of velocity of propagation at depth a to velocity at surface.
P = sound pressure causing motion of earth's surface.
$j = \sqrt{-1}$.

zone no doubt would be somewhere in between these extremes. Considering an area of 250 square miles, a plane flying at 250 m.p.h. in straight and level flight passing directly overhead would cause interference for approximately three and one-half minutes.

It is possible to estimate very roughly what the duration of interference from different types of airplanes is, assuming a single airplane in straight level flight passing directly overhead. As previously stated, one method of roughly estimating the acoustic power radiated is to assume a radiation efficiency of about 0.02% of the engine horsepower. Having the acoustic power, we can estimate the radius of interference and then by taking into account the airplane's speed, we can estimate the duration of interference. The following table based on the above procedure, except that the effect of altitude has not been taken into account, has been prepared by selecting several airplanes from Lester Ott's "Aircraft Spotter," 1943 Edition (Harcourt, Brace & Co., N. Y.). From this table it appears that the smallest airplanes will be responsible for about two minutes' interference and the largest airplanes about seven minutes. As a practical proposition, however, airplanes are apt to be executing maneuvers, and flying anything but a straight course. Not one, but several planes are apt to be in the vicinity, so that it is readily possible for the airplane interference to last an indefinitely long time. Moreover, the use of aircraft is so extensive at the present time that their interference is apt to be encountered even in regions remote from airfields.

Airplane			M.P.H. Top Speed	No. Engines	Engine Rated H.P.	Watts Acoustic Power	Estimated Minutes of Interference
Fairchild	PT-19A	Cornell	135	1	175	19	2.2
Curtis	Snc-1	Falcon*	215	1	450	50	2.3
Curtis	AT-9	Trainer	200	2	280	63	2.7
Douglas	R3D-2	Cargo	250	2	900	200	3.9
Lockheed	P-38	Lightning	400	2	1050	236	2.6
Douglas	DB-7B	Boston	350	2	1600	360	3.7
Consolidated	B-24	Liberator	300	4	1200	530	5.2
Lockheed	C-69	Constellation	300	4	2000	885	6.8

* Military version.

DISCUSSION OF METHODS SUGGESTED FOR MINIMIZING INTERFERENCE

A brief consideration of the obvious measures which might be attempted to minimize the interference may be of some interest.

1. *Frequency Discrimination:* This simple attack appears to offer

no promise. If a band elimination filter were used, it would have to eliminate all of the band from about 45 c.p.s. up to about 90 c.p.s. This conclusion is obvious from a consideration of the Doppler effect, as shown in Fig. 4.

2. *Microphone Responding to Air Sound Pressures Only Used to Balance Out Airplane Noise Picked Up by the Geophone:* A variable electrical network working on the output of the air microphone could be adjusted to produce a voltage of equal magnitude to that of the geophone, but of 180° phase difference. This method should work in principle. The electrical network balance would have to be made anew for each geophone plant.

3. *Use of a Sound-Proof Igloo over Each Geophone:* The elimination of the direct sound pressure applied to the geophone should help considerably, but certainly would not be good enough. It would be necessary to have the igloo essentially air-tight. This would necessitate an almost perfect seal between the igloo and the ground. The igloo itsef must be rigid to all frequencies below perhaps 200 c.p.s.

4. *Shoot Larger Charges.*

5. *Bury the Geophones:* This should help mainly by planting the geophones in the higher velocity soil encountered a foot or two below the surface. Loose dirt filled in the hole on top of the geophones probably would not be effective in stopping the penetration of the low frequency sound pressures down to the geophones. However, a rigid, airtight cover put over the hole and properly sealed with mud ought to be of considerable help.

It is realized that none of the obvious remedies suggested above comes anywhere near the answer to the problem. The only alternative is to wait until the planes pass out of range.

ACKNOWLEDGMENT

The writer gratefully acknowledges the Naval Ordnance Laboratory's encouragement of this work and the clearance which it obtained for the publication of this paper.

DEPTH-DISPLACEMENT SLIDE RULE*

W. R. FILLIPPONE†

ABSTRACT

A slide rule is described, based on formulae for circular arc ray paths, to compute depth and displacement of seismic reflectors when time of reflection, angle of dip and velocity-depth distribution are known. The rule may be used to compute horizontal and vertical displacement for reflectors on point-plotted sections if dips do not exceed fifteen degrees. An alternative is a modification of a standard log-log trig slide rule, which serves the same purpose.

GENERAL PROCEDURE

The depth-displacement slide rule is based upon the method and formulae for circular arc ray path plotting described by Peterson.[1] Plotting by this method consists of using two values, "h" and "R," where "h" is the depth below datum of the center of the spherical wave, and "R" is the radius of the sphere for a particular time of reflection. The formula for maximum depth is:

$$Z_{max} = (V_0/a)(e^{aT_0/2} - 1) \qquad (e = \text{natural log base})$$

where V_0 is the initial velocity at datum, a is the increase of velocity with respect to depth, and T_0 is the time of the reflection. The depth Z is comprised of the sum of two functions;

$$h = (V_0/a)(\cosh aT_0/2 - 1) \quad \text{and} \quad R = (V_0/a) \sinh aT_0/2.$$

For reflectors of zero degrees dip;

$$Z = h + R.$$

However, if the reflector has any degree of dip, "θ," the true depth is;

$$Z_\theta = h + R \cos \theta.$$

The horizontal displacement, d, for any reflector which is not directly below the shot point (i.e., a reflector with a non-zero dip) may be found from the R function and is given (see Fig. 1) by

$$d = R \sin \theta.$$

* Read by title at meetings of the Society, 1945.

† United Geophysical Co., Pasadena, Calif.

[1] R. A. Peterson: "A Transformed Wave Front Chart," GEOPHYSICS VI, pp. 74–80, 1941.

Use of the slide rule is not limited to the direct computation of depth and displacement. It can also be used to migrate (or offset) reflections on sections that are point-plotted. In such cases, the angle of

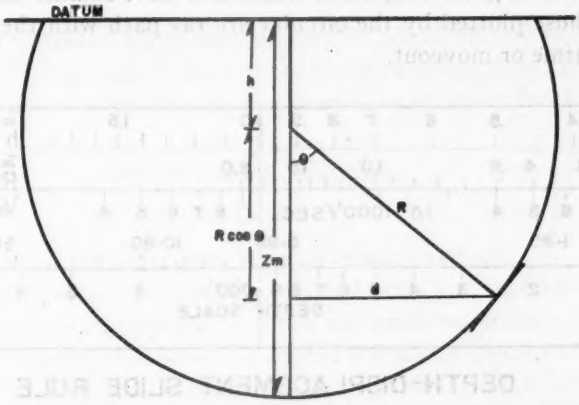


FIG. 1. Equal time circle and geometric relations for design of slide rule.

the plotted reflection must be measured and the center trace time must be known. From these two values, the horizontal displacement can be found by use of the formula just above. By using d, the amount of vertical displacement can be computed (see Fig. 2) as

$$v = d \tan \theta/2.$$

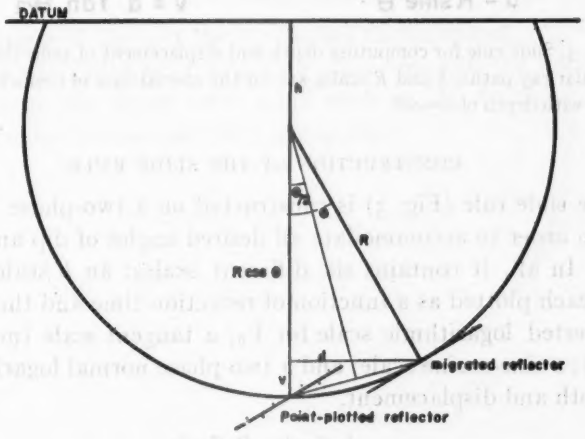
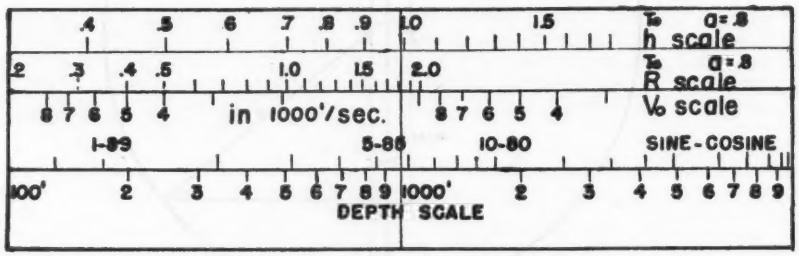


FIG. 2. Equal time circle and geometric relations for calculation of vertical displacement.

This method is valid for point-plotted dips of fifteen degrees or less. For point-plotted reflections with greater than fifteen degree dips, the point-plotted dips are less than those plotted by the circular arc ray path, resulting in a migration which will have smaller displacements than those plotted by the circular arc ray path with the same differential time or moveout.



DEPTH-DISPLACEMENT SLIDE RULE

$$V_z = V_o + aZ$$

$$Z_{max} = \frac{V_o}{a}(e^{aT_o/2} - 1) \qquad h = \frac{V_o}{a}(\cosh aT_o/2 - 1)$$

$$R = \frac{V_o}{a} \sinh aT_o/2 \qquad Z_\theta = h + R\cos\theta$$

$$d = R\sin\theta \qquad v = d \tan\theta/2$$

FIG. 3. Slide rule for computing depth and displacement of reflecting horizons using circular ray paths; h and R scales are for the special case of coefficient of increase of speed with depth of $a = 0.8$.

CONSTRUCTION OF THE SLIDE RULE

The slide rule (Fig. 3) is constructed on a two-phase logarithmic scale in order to accommodate all desired angles of dip and reflection times. In all, it contains six different scales: an h scale and an R scale, each plotted as a function of reflection time and the "a" value; an inverted logarithmic scale for V_0; a tangent scale (not shown in Fig. 3); a sine-cosine scale; and a two-phase normal logarithmic scale for depth and displacement.

h Scale: R Scale

The h scale and the R scale are based upon the formulae for h and

R, letting the velocity equal one thousand feet per second A different h and R scale must be made for each different a value.

Velocity (V_0), Tangent, Sine-Cosine, and Depth-Displacement Scales

These are standard scales such as may be found on any slide rule though it is of advantage to have them on a two-phase slide rule. The velocity scale is an inverted scale and is used as an index for the time function.

How to Use the Slide Rule

A. Depth

Given: time of the reflection, V_0, and the angle of dip.

1) Set V_0 opposite the time, T_0, on the h scale and read the value of h on the Depth scale opposite an index on the sliding scale.

2) Set V_0 opposite the time, T_0, on the R scale and read the value of $R \cos \theta$ on the Depth scale opposite the cosine of the angle of dip, θ.

3) Add the answers of 1 and 2 to get the true depth, Z_θ.

B. Horizontal Displacement

Given: Angle of dip and the time, T_0.

1) Set the velocity, V_0, opposite the time, T_0, on the R scale and read the value of $R \sin \theta$ on the Displacement scale opposite the sine of the angle of dip, θ.

C. Vertical Displacement

Given: Angle of dip and the horizontal displacement.

1) Line up an index on the sliding scale opposite the horizontal displacement on the depth scale. Read back on the depth scale opposite the tangent of one-half the angle of dip.

PATENTS*

ELECTRICAL PROSPECTING

U. S. No. 2,382,093. S. R. Phelan. Iss. 8/14/45. App. 3/7/42.

Method for Making Geophysical Surveys. A method of electrical prospecting using a group of equal current electrodes of like polarity separated by distances of the same order as the distance to the electrodes of opposite polarity, and measuring the potential variations at fixed pick-up electrodes when the various input electrodes are disconnected from the circuit.

GEOCHEMICAL PROSPECTING

U. S. No. 2,382,992. J. S. Harris. Iss. 8/21/45. App. 2/10/44.

Soil Sampling Apparatus. A soil sampling machine having an outer cutting pipe and an inner water supply pipe, the assembly being washed into the ground after which the inner pipe is held and the cutting pipe forced down further to take the sample.

GRAVIMETRIC PROSPECTING

U. S. No. 2,383,966. A. F. Hasbrook. Iss. 9/4/45. App. 3/18/43. Assign. Olive S. Petty.

Geophysical Prospecting Apparatus. An underwater gravimeter having an instrument suspended on self leveling gimbals and having clamping motors which may be started from the surface and which have automatic limit switches.

U.S. No. 2,383,997. R. C. Sweet. Iss. 9/4/45. App. 12/29/43. Assign. Stanolind Oil and Gas Co.

Gravity Meter. A horizontal beam gravity meter having a zero length spring pulling at an angle and attached at its upper end to an elastic support which is moved by adjusting a second spring also attached to the support.

U. S. No. 2,384,739. A. F. Hasbrook. Iss. 9/11/45. App. 3/18/43 and 2/9/44. Assign. Olive S. Petty.

Geophysical Prospecting Apparatus. An underwater gravimeter having an inner instrument case suspended on self leveling gimbals and having electronically controlled motors for balancing the instrument case to bring it into exact level position.

MAGNETIC PROSPECTING

U. S. No. 2,379,716. A. W. Hull. Iss. 7/3/45. App. 9/16/43. Assign. General Electric Co.

Magnetic Field Gradient Meter. Apparatus for measuring magnetic gradient and having two high permeability cores excited by a-c with a d-c indicating instrument and a nonlinear resistance in series with them, a long external solenoid being used to neutralize the average ambient field, and a short coil to set up a calibrating gradient.

U. S. No. 2,383,459. L. F. Beach. Iss. 8/28/45. App. 7/30/40. Assign. Purves Corp.

Indicator for Magnetic Fields. A remote direction indicating magnetic compass system having three flux valves oriented at 120° and connected to a direction indicating instrument of the Selsyn type.

* Abstracts by O. F. Ritzmann, Gulf Oil Corporation Patent Department.

U. S. No. 2,383,460. J. C. Purves and L. F. Beach. Iss. 8/28/45. App. 3/28/41. Assign. Purves Corp.

Magnetic Field Responsive Device. A flux valve type transmitter for a remote indicating magnetic compass in which three or more flux valves are excited from a single core which also serves as a support.

U. S. No. 2,383,461. O. E. Esval, R. S. Curry, C. F. Fragola and L. F. Beach. Iss. 8/28/45. App. 10/10/41. Assign. Sperry Gyroscope Co., Inc.

Flux Valve Compass System. A flux valve magnetic compass system for aircraft using two pendulum mounted flux valve type transmitter units symmetrically mounted and having their outputs combined to average out errors due to yawing of the ship.

U. S. No. 2,384,819. M. C. Depp. Iss. 9/18/45. App. 1/19/43. Assign. Sperry Gyroscope Co., Inc.

Flux Valve. A flux valve type transmitter for a remote indicating magnetic compass in which three flux valves are arranged with their cores forming a triangle.

SEISMOGRAPH PROSPECTING

U. S. No. 2,383,571. E. M. Shook. Iss. 8/28/45. App. 2/1/38 and 4/15/43. Assign. Socony-Vacuum Oil Co., Inc.

Gain Control for Seismograph Amplifiers. A time-gain control for seismograph amplifiers which initially is at full sensitivity and in which a first arrival fires a thyratron to complete a condenser charging circuit whose IR drop changes the amplifier grid bias to reduce sensitivity..

U. S. No. 2,384,393. J. O. Parr, Jr. Iss. 9/4/45. App. 8/4/43. Assign. Olive S. Petty.

Stabilizer for Automatic Volume Control Circuits. A signal operated volume control circuit in which ripple voltage is cancelled by adding to the control voltage a ripple of opposite phase obtained from a transformer.

U. S. No. 2,384,851. C. Reichert. Iss. 9/18/45. App. 9/21/43. Assign. Olive S. Petty.

Method of Seismic Surveying. A method of delaying the blowing out of seismograph shot holes by plugging the upper end of the hole only.

WELL LOGGING AND SURVEYING

U. S. No. 2,379,757. L. F. Smith. Iss. 7/3/45. App. 11/9/44. Assign. One-half to J. C. McWhorter.

Core Retriever. A tool for recovering cores lost from a core barrel which has a downward extension to work the cores into the tool and an upward facing shoulder with a spring finger to keep the cores in place.

U. S. No. 2,379,996. D. Silverman. Iss. 7/10/45. Appl. 4/29/42. Assign. Stanolind Oil and Gas Co.

Transmitting System. A method of transmitting an amplitude modulated signal up a well logging cable by simultaneously also transmitting a standard signal and automatically correcting the received unknown amplitude according to variations in the received standard signal.

U. S. No. 2,380,520. G. L. Hassler. Iss. 7/31/45. App. 4/24/42 and 3/25/44. Assign. Shell Development Co.

Borehole Indicating Apparatus. A system for acoustically transmitting through the well fluid an indication of two borehole variables by having one variable control the duration of an acoustic signal generated in the hole and the other variable control the duration of silence between signals, and recording the signals at the surface.

U. S. No. 2,381,844. J. C. Stokes. Iss. 8/7/45. App. 5/11/42. Assign. Reed Roller Bit Co.

Core Taking Apparatus. A core barrel having a differential piston at its upper end to hold the inner core barrel in place when under hydraulic pressure.

U. S. No. 2,381,845. J. C. Stokes. Iss. 8/7/45. App. 5/11/42. Assign. Reed Roller Bit Co.

Pressure Core Drilling Apparatus. A pressure core barrel in which the inner core barrel is carried on a piston, hydraulic operation of which is initiated by dropping a valve plug, the piston raising the inner barrel above a lower flap valve and closing an upper sleeve valve to seal the barrel.

U. S. No. 2,381,904. D. G. C. Hare. Iss. 8/14/45. App. 10/16/41. Assign. The Texas Co.

Method and Apparatus for Logging Wells. Radioactivity logging apparatus which is supplied low frequency power by a two wire cable and whose indication is fed to the surface over the same wires by a high frequency current generated and modulated in the instrument and detected at the surface.

U. S. No. 2,382,279. A. Wolf and G. Herzog. Iss. 8/14/45. App. 11/27/43. Assign. The Texas Co.

Device for Recovering a Radiation Source. A device for attaching a radiation source to the cable of a well logging instrument so that if the instrument becomes stuck the cable and radiation source will separate from the instrument and may be withdrawn.

U. S. No. 2,382,609. C. R. Dale. Iss. 8/14/45. App. 12/16/40. Assign. 13.75% to J. R. Pemberton and 45% to Technical Oil Tool Corp., Ltd.

Recording Instrument for Oil Wells. A recorder for a self contained well logging instrument in which the measuring element controls the length of a light slit whose image is periodically recorded photographically as a transverse line on a photographic strip.

U. S. No. 2,383,455. H. G. Abadie. Iss. 8/28/45. App. 11/28/42. Assign. One-half to F. G. Bradbury.

Method and Apparatus for Locating Leaks in Wells. A thermal method of locating leaks between outer and inner casing strings by pumping in a large volume of gas at a pressure sufficient to discharge through the leak and running a temperature log to locate the resulting temperature anomaly.

U. S. No. 2,384,648. D. Silverman. Iss. 9/11/45. App. 1/14/42. Assign. Stanolind Oil and Gas Co.

Locating Bottom of Oil Production. A method of locating the lowest oil producing horizon in a well by displacing the well fluid by an oil-miscible non-conducting water-

immiscible fluid heavier than salt water, producing the well to wash out this fluid above the lowest oil production and subsequently running an electric log of the fluid to locate the interface.

U. S. No. 2,384,840. S. Krasnow and L. F. Curtiss. Iss. 9/18/45. App. 4/16/37 and 10/20/41. Assign. Geophysical Development Corp.

Radioactive Well Logging Method and Apparatus. A radioactivity well logging device in which ionization pulses through the detecting element operate a relay in the well apparatus, the relayed pulses being transmitted to the surface over a cable and recorded.

U. S. 2,385,378. R. G. Piety. Iss. 9/25/45. App. 6/11/42. Assign. Phillips Petroleum Co.

Well Surveying. A method of relative permeability well logging by applying pressure to force fluid into the formations, ejecting a radioactive sample above the open hole portion of the well, tracing the sample down with a radioactive detector and subsequently running a radio-activity log of the well.

MISCELLANEOUS

U. S. No. 2,379,782. L. J. Bobb. Iss. 7/3/45. App. 9/11/43. Assign. Philco Radio and Television Corp.

Phonograph Pickup. A moving coil, permanent magnet, dynamic type phonograph pickup which may play either lateral-cut or hill-and-dale recordings by a simple rotation of the magnet.

U. S. No 2,379,897. F. K. Floyd. Iss. 7/10/45. App. 6/3/42. Assign. Claude M. Hathaway.

Amplifier System. A carrier wave amplifying system in which the carrier is applied to a bridge with the modulating signal applied to one leg through rectifiers, the bridge unbalance being amplified and the output rectified.

U. S. No. 2,380,249. H. P. Kuehni. Iss. 7/10/45. App. 5/11/44. Assign. General Electric Co.

Liquid Level Indicating Device. A liquid level gauge having a loosely wound spiral gauge tube and an indicator to show changes in the spiral pitch caused by the weight of liquid in the tube.

U. S. No. 2,380,251. L. C. Ludbrook. Iss. 7/10/45. App. 7/13/43 and 7/11/44. Assign. General Electric Co.

Electromagnetic Gauge. A carrier current magnetic bridge type of gauge in which the output is applied to a demodulating bridge energized by the same carrier and indicated on a d-c instrument.

U. S. No. 2,380,399. H. J. Bowie. Iss. 7/31/45. App. 6/10/43. Assign. Fisher & Porter Co.

Flowmeter. A rotameter type flowmeter whose float has a magnet which drags a follower magnet mechanically connected to the transmitting unit of a remote indicator.

U. S. No. 2,380,433. M. Hattan. Iss. 7/31/45. App. 9/13/44.

Tensiometer. A cable tensiometer in which the clamping element and the deflecting element act on the same side of the cable and which is calibrated so that tension may be measured by applying a torque wrench to produce an indicated deflection.

U. S. No. 2,380,439. E. E. Hoskins and R. V. Langmuir. Iss. 7/31/45. App. 4/6/42. Assign. Consolidated Engineering Corp.

Mass Spectrometer. A recording mass spectrometer with automatic beam sweep and in which the ion current is recorded on a tape by several galvanometers having graduated sensitivities, so that small and large peaks may be accurately measured.

U. S. No. 2,380,514. K. J. Germeshausen. Iss. 7/31/45. App. 6/12/40.

Vibration-Translating Device. A phonograph pick-up having a stylus made of an insulator with a thin conducting surface of graphite whose resistance varies as the stylus vibrates.

U. S. No. 2,381,036. M. Camras. Iss. 8/7/45. App. 8/10/42. Assign. Armour Research Foundation.

Safety Timing Mechanism for Magnetic Recorders. A device for stopping a magnetic tape recorder at a desired point by footage controlled switches or near the end by having the tape break the motor circuit.

U. S. No. 2,381,283. C. M. Hathaway. Iss. 8/7/45. App. 11/8/43. Assign. Hathaway Instrument Co.

Means for Mounting Testing Apparatus. A method of attaching an electric strain gage to a member by means of hooks cemented to the surface of the member and elastic bands to hold down the gage.

U. S. No. 2,381,463. R. K. Potter. Iss. 8/7/45. App. 2/7/44. Assign. Bell Telephone Laboratories, Inc.

Magnetic Sound Record. A magnetic record in the form of a grooved disk, the magnetic material being formed on the land between grooves and the pick-up device having two poles which ride in adjacent grooves.

U. S. No. 2,381,990. C. Stevens. Iss. 8/14/45. App. 2/17/43.

Means for Detecting Structural Flaws in Sheet Material. A device for measuring the thickness of paper or textile in which a contact roller and lever move one plate of a condenser connected in one side of a balanced induction bridge and the unbalance amplified.

U. S. No. 2,382,351. J. B. Thorpe. Iss. 8/14/45. App. 6/11/41.

Extensometer. A device for measuring tension in a twisted cable by indicating on an annular scale the changes in twist between two clamps.

U. S. No. 2,382,516. P. T. Sprague. Iss. 8/14/45. App. 3/29/43. Assign. The Hays Corp.

Liquid Level Follow-Up Device. An electrode unit for contacting the upper surface of a conducting liquid and having a wire inside a capillary tube, contact to the liquid body being made by a drop of liquid held on the end of the tube by surface tension.

U. S. No. 2,382,547. K. J. De Juhasz. Iss. 8/14/45. App. 2/7/41.

Maximum Pressure Gauge. An engine cylinder maximum pressure gauge in which the pressure moves a small spring loaded piston, the other end of the spring having measured adjustable hydraulic loading and movement of the piston being indicated through an electric contact.

U. S. No. 2,382,692. A. Courcy and M. P. Durand. Iss. 8/14/45. App. 10/24/41 and 8/14/42. Vested in Alien Property Custodian.

Mechanical-Electrical Sound Reproducer. A carbon button type phonograph pick-up in which the stylus is supported by conical spiral spring connections to the carbon buttons.

U. S. No. 2,382,743. C. J. Penther and F. B. Rolfson. Iss. 8/14/45. App. 1/26/42. Assign. Shell Development Co.

Electromagnetic Apparatus for Pipe-Line Surveys. Apparatus for magnetically measuring pipe line currents by having two spaced inductor coils rotated synchronously in opposite directions to cancel effect of the earth's field and having one coil close above the pipe line and the other coil at some distance.

U. S. No. 2,382,979. K. Demb. Iss. 8/21/45. App. 6/24/44. Assign. Sylvania Electric Products, Inc.

Viscometer. A continuously indicating viscosity meter in which a sample flows into a rotating cup and the level maintained by an outer overflow cup, the recording pen being carried on a shaft having paddles in the liquid and acting against a spiral spring.

U. S. No. 2,383,075. O. W. Pineo. Iss. 8/21/45. App. 4/29/42. Assign. American Cyanamid Co.

Spectrophotometer. A flickering beam spectrophotometer with a-c operated light source and in which the signal due to variation in light intensity is removed by a rejection circuit in the amplifier.

U. S. No. 2,383,346. W. A. Shurcliff. Iss. 8/21/45. App. 5/20/44. Assign. American Cyanamid Co.

Spectrophotometer Attachment for Eliminating Specular Reflection. A transparent adapter through which one of the beams of a flickering beam spectrophotometer may be transmitted through the integrating sphere to the sample, and arranged so that specular reflectance from the sample is transmitted to the outside of the sphere.

U. S. No. 2,383,542. E. A. Godfrey. Iss. 8/28/45. App. 3/19/43.

Paper Container for Dynamite. A male and female threaded paper container for making up long dynamite charges, the dynamite sticks having an annular reduced neck which fits the reduced inside diameter of the male end of the container to hold the sticks in place.

U. S. No. 2,383,757. H. Ziebolz. Iss. 8/28/45. App. 5/23/42. Assign. Electronbeam, Ltd.

Force Measuring Apparatus. A device for measuring differential pressure, level, etc. inside a pressure-tight casing by having the measured force affect the position of a magnet carried on a Kelvin balance, the magnet field outside the casing changing the electron path in a tube whose plate current is amplified and returned to the Kelvin balance to restore equilibrium.

U. S. No. 2,383,758. H. Ziebolz. Iss. 8/28/45. App. 9/23/43. Assign. Electronbeam, Ltd.

Electronic Translating Device. A device for translating a condition into electrical indication in which the condition responsive element has a moving magnet whoes external field affects the electron path in a tube whose anode current is indicated.

U. S. No. 2,383,820. S. Rosenblum. Iss. 8/28/45. App. 12/8/42. Assign. Canadian Radium & Uranium Corp.

Apparatus and Method of Utilizing Ionizing Radiations. A device for demonstrating the presence of alpha radiations and using a pair of high tension electrodes in air, the currrent pulses producing a visible flash or operating a sensitive relay.

U. S. No. 2,383,844. J. G. Bouslog. Iss. 8/28/45. App. 11/2/42.

Oil Well Bailer Line Measuring Device. A sand line measuring device having a base mounted on the well head, a counter wheel around which the cable passes and a traction wheel which may be disengaged.

U. S. No. 2,383,855. C. W. Hansell. Iss. 8/28/45. App. 12/10/42. Assign. Radio Corp. of America.

Potential Ratio-Controlled Amplifier. A beam type cathode ray tube having two deflecting electrodes connected to a balanced frequency modulated detector and two collector electrodes connected in push-pull to the audio output.

U. S. No. 2,384,529. V. W. Breitenstein. Iss. 9/11/45. App. 7/27/40. Assign. Illinois Testing Laboratories, Inc.

Magnetic Instrument. A device for indicating the presence or thickness of magnetic material or non-magnetic coatings and having a permanent magnet, adjustable leakage circuit and pivoted magnetic vane with pointer which changes position as the field is disarranged by the material tested.

U. S. No. 2,384,534. O. E. Chenoweth and P. F. Lewis. Iss. 9/11/45. Appl. 7/23/41. Assign. E. I. duPont de Nemours & Co.

Explosive Dump Shell. A shell for loading explosive in a well by a cable and having a drop bottom attached by a drop link which is released when the shell hits the bottom of the well.

U. S. No. 2,384,586. F. J. Allgeo. Iss. 9/11/45. App. 7/20/43.

Level. A mechanical level having a pendulum suspended on needle bearings and a transparent scaled dome against which a pendulum pointer is read.

U. S. No. 2,384,716. A. M. Wengel. Iss. 9/11/45. App. 3/14/41. Assign. Ray-O-Vac Co.

Frequency Responsive Indicating Apparatus. A vibration testing circuit in which a rapidly varying beat frequency is applied to a vibrator on the member and the excited frequency picked up and observed on an oscilloscope.

U. S. No. 2,385,005. B. F. Langer. Iss. 9/18/45. App. 11/19/42. Assign. Westinghouse Electric Corp.

Strain Measuring System. A system for measuring the torque output of an airplane engine by supporting the engine through two parallel coaxial rings and measuring their relative angular deflection with a magnetic strain gauge.

U. S. No. 2,385,424. C. L. Shue and F. J. Allgeo. Iss. 9/25/45. App. 10/9/42.

Level. A mechanical level having a pendulum hung on a pivot or ball joint and a transparent scaled dome against which a pendulum pointer is read.

DISCUSSIONS AND COMMUNICATIONS

STATUS OF THE FEDERAL EXPLOSIVES ACT

Because of recent statements in the press and the elimination of the office of licensing agents, many persons are confused regarding the status of the Federal Explosives Act. This Act is still in full force, and any person violating its provisions is still subject to the penalties provided.

On October 5, 1945, the Bureau of Mines issued General License No. 8 which reads as follows: "A general license is hereby granted under the Federal Explosives Act of December 26, 1941 (55 Stat. 863), as amended, to any person as defined in the act and regulations, who is not otherwise prohibited by law or by regulation or by proclamation of the War Department, the Attorney General, or any other Federal agency from doing so, to manufacture, distribute, possess, purchase, accept, receive, acquire, store, sell, issue, or otherwise dispose of and use explosives and ingredients, as defined in the act and the regulations. This general license relieves persons covered by it from the duty of applying for and securing licenses under the Federal Explosives Act and the regulations. The authority of licensing agents under the Federal Explosives Act and regulations to issue licenses is hereby suspended until this general license shall have expired. This general license shall expire when revoked by the Director of the Bureau of Mines or when the Federal Explosives Act and the regulations are of no further force or effect, whichever happens first." (The Solicitor's office of the Bureau of Mines has given an opinion that under this license persons under 21 years of age may possess explosives.)

In other words, there have been no changes made in the Federal Explosives Act except that everyone operates under General License No. 8, and it is not necessary or possible to secure company or individual licenses. This does not prevent the Bureau of Mines from enforcing any provisions of the Act or after due process of law from stopping a violator from purchasing, possessing, storing, transporting, or using explosives.

All explosives accidents must be reported to the Bureau of Mines as soon as possible after their occurrence; records of explosives must be kept; and storage facilities must be maintained as provided by the Act. Parties that are not reporting accidents direct to the Bureau of Mines, have stopped keeping records, or have removed the lining from the magazines should correct these conditions or any other changes they have made which are contrary to the provisions of the Act.

The Federal Explosives Act will remain in effect until the war is officially over or action is taken by Congress or the President.

G. M. Kintz
Supervising Engineer, District G
Health and Safety Branch
Bureau of Mines
U. S. Department of the Interior
Dallas, Texas

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World Petroleum, Vol. 16, Nos. 11, 12, and 13 (Oct., Nov., and Dec., 1945) Vol. 17, No. 1 (January).

"Navy Pushing Tests of Alaskan Reserve" (Oct.)

"Geologic Surveys are Planned for Continental Shelf." (Nov.)

"On Some New Permian Fossils from the Magnesian Limestone near Sunderland." By C. T. Trechmann. Reprinted from the *Quarterly Journal of the Geological Society of London*, Vol. c, pp. 333–354, and plate XV, published 31 March, 1945.

"The West Indies and the Mountain Uplift Problem." By C. T. Trechmann. Privately printed by Messrs. B. T. Ord Limited, West Hartlepool, May 1945.

CONTRIBUTORS

C. Y. Fu

B.S. in physics, 1933, National Tsing Hua University, China. M.Sc. in physics and geophysics, 1941, McGill University, Canada. Ph.D. in geophysics, 1944, California Institute of Technology.

Assistant in physics, 1934–1938, Tsing Hua University, Instructor in physics, 1938–1940, Tsing Hua University, Sino-British Indemnity Fund Scholarship, 1939–1943, Assistant in geophysics, 1941, Colorado School of Mines, Teaching Fellow in geophysics, Cal. Tech. 1942–1944, Research Fellow in geophysics, 1944–, Cal. Tech.

Member of Sigma Xi, 1941, Member of A.I.M.E., 1945, Member of Chinese Physical Society, 1936.

A. J. Barthelmes

A. J. Barthelmes attended the Technical Universities in Munich and Darmstadt, where he received his C.E. degree in 1925. After completing post-graduate work at the Universities of Berlin and Braunschweig, he received his degree of Doctor of Engineering in 1932. From 1933 to 1935 he was employed by the Shell Petroleum Corporation as Seismologist. Since 1935 he has been associated with Seismograph Service Corporation.

Dr. Barthelmes is a member of the Society of Exploration Geophysicists, the American Association of Petroleum Geologists, and the American Geophysical Union.

DR. SIDON HARRIS

Sidon Harris received his B.A. degree in physics from the University of Texas in June, 1929, his M.A. degree from the same institution in August, 1929, and his Ph.D. degree from the University of Texas in June, 1934. His major for his doctorate was experimental physics, his minors were in mathematical physics and geophysics. He has published a number of articles in scientific journals on the following subjects: Piezo-electricity, X-rays, Conductivity of gases, Geophysics.

He was a member of the seismograph department of the Stanolind Oil & Gas Company for ten years, the last five of which he served as Supervisor of the North Texas-New Mexico division. He opened offices as a consulting geophysicist in November, 1944, in Fort Worth, Texas. In March, 1945, he was named president of the Southern Geophysical Company, which position he now holds. He is a member of the American Physical Society, The American Association of Petroleum Geologists, the Society of Exploration Geophysicists, Phi Beta Kappa, and Sigma Xi. Before becoming associated with Stanolind, he was a member of the geophysical department of the Humble Oil Company and served on the faculties of the University of Texas, Rice Institute, and Oklahoma A & M.

Miss Gwendolyn Peabody entered the geophysical profession in 1942 when she was employed by the seismograph department of Stanolind Oil and Gas Company. Here she became the first woman computer in the North Texas-New Mexico division. She remained with Stanolind until November, 1944 at which time she joined Southern Exploration Service. In May 1945 she was named secretary-treasurer of Southern Geophysical Company. Miss Peabody is a member of the Society of Exploration Geophysicists.

GWENDOLYN PEABODY

J. M. Kendall received his B.S. degree from The Rice Institute in 1925. He was employed by the Radio Department of the General Electric Company, Schenectady, N. Y., from 1925 to 1930. He was transferred to the R.C.A.-Victor Mfg. Co., Camden, N. J., in 1930 where he worked on development of phonograph equipment until 1934. From 1934 to 1941 he was employed by the laboratory of the Geophysical Research Corp. From 1941 to the present he has been engaged in war work at the Naval Ordnance Laboratory, Washington, D. C.

J. M. KENDALL

PETER E. NARVARTE

Peter E. Narvarte received the degree of B.S. in C.E. from the University of Texas in 1932. He has been associated with the Petty Geophysical Engineering Company since 1934.

After devoting five years to seismic exploration work in which he attained respectively the positions of Computer and Seismologist, he joined the supervisory staff of the Petty Company in 1939. Since that time he has been engaged in the interpretation of seismic data and the development of improved methods of computation. In that connection, he has performed the duties of Chief Seismologist and Supervisor in which latter capacity he is now employed.

He is a member of Tau Beta Pi, and the Society of Exploration Geophysicists.

Walter Ross Fillippone received the A.B. degree from Marietta College in 1942, major in geology, and the M.S. degree from the California Institute of Technology in 1944, major in geophysics. In the fall of 1943, he was employed by the United Geophysical Company in Pasadena, California, and, after receiving his degree in 1944, he became chief computer on a field party.

WALTER ROSS FILLIPPONE

Photographs and biographies of contributors to this issue not appearing above have been published previously, as follows: E. D. Alcock, Vol. VII, No. 4, p. 426 (October, 1942). J. A. Gillin, Vol. VIII, No. 1, pp. 78–79 (January, 1943).

THE SOCIETY ROUND TABLE

ANNOUNCEMENT OF THE SIXTEENTH ANNUAL MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

The sixteenth annual meeting will be held in Chicago, April 1–4, in cooperation with the American Association of Petroleum Geologists and the Society of Economic Paleontologists and Mineralogists. Headquarters for all societies will be The Stevens Hotel.

The general program is as follows:

MONDAY, APRIL 1	*Morning*	S.E.G. Annual Business Meeting, Announcement of Election of Officers, Technical Session.
	Afternoon	S.E.G. Technical Session
	Evening	A.A.P.G. Research Committee
TUESDAY, APRIL 2	*Morning*	Joint Session, S.E.G., A.A.P.G., and S.E.P.M. Presidential Addresses, etc.
	Afternoon	Technical Sessions—S.E.G., A.A.P.G., S.E.P.M.
	Evening	A.A.P.G.—Guest Speaker
WEDNESDAY, APRIL 3	*Morning*	Technical Sessions—A.A.P.G., S.E.P.M.
	Afternoon	Technical Sessions—A.A.P.G., S.E.P.M.
	Evening	Dinner—Dance
THURSDAY, APRIL 4	*Morning*	Technical Sessions—A.A.P.G., S.E.P.M.
	Afternoon	Technical Sessions—A.A.P.G., S.E.P.M.

Hotel arrangements should be made directly with The Stevens Hotel. When their space is exhausted, inquiries will be turned over by them to other hotels. Members planning to attend are urged to complete hotel arrangements as soon as possible and should not plan to come to Chicago without a confirmed reservation.

Papers for the S.E.G. program and for subsequent publication in GEOPHYSICS should be announced as soon as possible. There will be a combined printed program containing title, author's name, address, company connection, and abstract of each paper. To be included in this program, the above material should reach the Chairman of the Program Committee by February 25. Members are urged to prepare papers for reading at the meeting or for listing by title, as such material is the principal source upon which GEOPHYSICS depends each year for its papers. Those having material of interest or knowing of any should get in touch with the regional committee members listed below.

COMMITTEES

General Chairman

J. J. Jakosky, 1063 Gayley Avenue, Los Angeles (Vice-Pres. S.E.G.)
Ira H. Cram, Pure Oil Company, Chicago (Advisory)

Regional Committees

Chicago Arrangements Committee

T. A. Manhart, *Chairman*, Seismograph Service Corporation, Tulsa
Ira H. Cram, Pure Oil Company, Chicago (Advisory)

L. O. Seaman, Sinclair-Prairie Oil Company, Tulsa
J. E. Hawkins, Seismograph Service Corporation, Tulsa

Regional Program Committees

Houston

Roy L. Lay, *Chairman*, The Texas Company
Ralph S. Jackson, Independent Exploration Company
W. J. Osterhoudt, Gulf Research & Development
Homer G. Patrick, Humble Oil and Refining Company
J. C. Pollard, Rogers-Ray, Inc.
W. Harlan Taylor, Petty Geophysical Engineering Company

Dallas

E. D. Alcock, *Chairman*, National Geophysical Company
W. W. Newton, Geotechnical Corporation
A. E. McKay, Atlantic Refining Company

Tulsa

L. Y. Faust, *Chairman*, Geophysical Research Corporation
Albert J. Barthelmes, Seismograph Service Corporation
R. Clare Coffin, Stanolind Oil and Gas Company

Fort Worth

James L. Morris, *Chairman*, Pure Oil Company
Ralph H. Lang, Gulf Research & Development Company
Paul H. Ledyard, Southern Geophysical Company

Shreveport

William M. Barret, *Chairman*, William M. Barret, Inc.
Richard M. Wilson, Ohio Oil Company
C. D. Keen, Consulting Physicist

New Orleans

Neal J. Smith, *Chairman*, The California Company
Joe B. Hudson, Humble Oil and Refining Company

Jackson

Ewin D. Gaby, Geophysical Service, Inc.

San Antonio

Thomas L. Allen, Petty Geophysical Engineering Company

Eastern

L. L. Nettleton, *Chairman*, Gulf Research & Development Company, Pittsburgh
Milton B. Dobrin, Naval Ordnance Laboratory, Washington, D. C.
D. C. Skeels, Standard Oil Company of New Jersey, New York

Pacific Coast

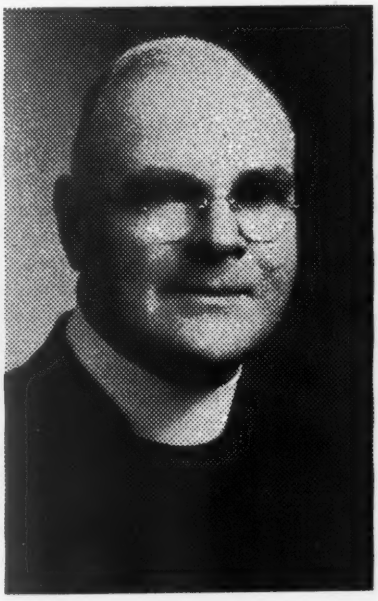
O. C. Lester, Jr., *Chairman*, Amerada Petroleum Corporation, Los Angeles, Calif.
Henry Salvatori, Western Geophysical Co., Los Angeles, Calif.
Phil P. Gaby, Geophysical Service, Inc., Fresno, Calif.
E. H. Vallat, Ohio Oil Company, Bakersfield, Calif.
C. H. Dresbach, Western Gulf Oil Company, Los Angeles, Calif.

NOMINEES FOR 1946–1947 EXECUTIVE COMMITTEE

The following brief biographical sketches are presented in an attempt to acquaint members of the Society with nominees appearing on the official ballot for the coming year. These biographical sketches are the same as were included in the folder mailed with official ballots.

FOR PRESIDENT

JOHN JAY JAKOSKY



JAMES B. MACELWANE, S.J.

JOHN JAY JAKOSKY was born at Vinita, Indian Territory (later Oklahoma) January 20, 1896. He received a B.S. in Mechanical Engineering at the University of Kansas in 1920, a B.S. in Electrical Engineering at the University of Pittsburgh in 1925, the Professional degree of Mechanical Engineer at the University of Kansas in 1926, and, after graduate work at the Carnegie Institute of Technology and the University of Arizona, a Doctor of Science degree from the latter in 1933. From 1920–25 he acted as Research Engineer for the U. S. Bureau of Mines, chiefly in studies of underground communication, sub-surface attenuation, and similar matters. From 1925–28 he occupied the position of Physicist for the Western Precipitation Company and the Research Corporation, engaged principally in devising equipment for eliminating radio interference caused by high voltage precipitators. For a period of two years he served as a Consulting Engineer for the Southwestern Engineering Corporation, investigating high frequency inductive methods for shallow mineral exploration. In 1929 he organized International Geophysics, Inc. In 1940 he resigned as President of International Geophysics to accept the position of Dean of the Schools of Engineering and Architecture and Director of the Engineering Experiment Station at the University of Kansas.

In 1943 he accepted his present position as Director of Industrial Research and Assistant to the President of the University of Southern California. On leave, his present activities are devoted almost wholly to research concerned with the war. He is the author of the text EXPLORATION GEOPHYSICS, and is a member of the American Institute of Mining and Metallurgical Engineers (serving as a member of the Committee on Geophysics, the Committee on Geophysics Education, and the Committee on Mining Education), the American Association of Petroleum Geologists, the American Geophysical Union, the Society for the Promotion of Engineering Education, and the Society of Exploration Geophysicists (Vice-President, 1945–46). Academic organizations include Sigma Xi, Tau Beta Pi, Sigma Gamma Epsilon, Pi Tau Sigma, Theta Tau, and Delta Upsilon.

JAMES B. MACELWANE, S.J., received his A.B. degree in 1910, his A.M. in 1911, and his M.S. in 1912 from St. Louis University. In 1923 he received the degree of Ph.D. in physics from the University of California. He held an assistantship in meteorology and seismology at Saint Louis University 1910–12 and an instructorship in physics 1912–13. He was appointed Assistant Professor of Physics at the same university 1913–15 and 1918–19. He acted as assistant in seismology at the University of California in Berkeley 1921–23 and was appointed Assistant Professor of Geology 1923–1925, being placed in charge of the seismograph stations and, further, organizing graduate studies in seismology. In 1925 he was called to Saint Louis University as Professor of Geophysics to organize the Department of Geophysics. He was appointed its Director and has remained in that position. In 1944 he was appointed Dean of the newly organized Institute of Geophysical Technology of Saint Louis University. Father Macelwane is a member of the National Academy of Science; a fellow of the Geological Society of America; a life member and Past President of the Seismological Society of America; a fellow of the American Association for the Advancement of Science, serving as Chairman of Section E, Geology and Geography, in 1934; a member of the American Geophysical Union, serving as President of the Section of Seismology 1938–41; a member of the American Physical Society, the American Meteorological Society, the American Geographical Society, the American Institute of Mining and Metallurgical Engineers, and the Society of Exploration Geophysicists. He is a Past President of the Missouri Academy of Science and also of the Academy of Science of Saint Louis. He was joint author with J. I. Shannon of A LOOSE-LEAF MANUAL OF LABORATORY EXPERIMENTS IN PHYSICS (Saint Louis University) joint author with F. W. Sohon of INTRODUCTION TO THEORETICAL SEISMOLOGY and wrote Volume I, GEODYNAMICS (John Wiley and Sons); editor and part author of SEISMOLOGY (Bulletin 90 of the National Research Council); and part author of INTERNAL CONSTITUTION OF THE EARTH (McGraw-Hill), edited by B. Gutenberg. He is author of WHEN THE EARTH QUAKES (Bruce, in press).

FOR VICE-PRESIDENT

CECIL H. GREEN received the degrees of S.B. and S.M. in Electrical Engineering in 1924 from the Massachusetts Institute of Technology. Until 1926 he was a development engineer in the A.C. Engineering Department, General Electric Company, Schenectady. During this period he also served as an instructor in advanced engineering classes. He then became Research Engineer for Raytheon Manufacturing Company,

engaged in the development of Gaseous Discharge rectifier devices. In 1928 he became Development Engineer with Federal Electric Company, finally being placed in charge of the transmitting tube division of the Newark plant. He entered Geophysical Service, Incorporated, in 1930, serving as party chief until 1936 and as district supervisor until 1941, when he was made Vice-President. He is a member of the American Association of Petroleum Geologists and of its National Committee on Applications of Geology,

CECIL H. GREEN

C. A. HEILAND

Vice-President of the Dallas Geological Society, and a member of Dallas Petroleum Club, the Society of Exploration Geophysicists (Secretary-Treasurer, 1945–46), and the American Geophysical Union.

C. A. HEILAND received his Sc.D. degree from the University of Hamburg in 1923. He engaged in magnetometer work for the State of Hamburg in 1921, and conducted torsion balance surveys for the Raky Drilling Company while at the University of Heidelberg from 1922 to 1923. He resigned from this company in 1924 to take charge of the Geophysical Department of the Askania Werke in Berlin. In the following year he came to the United States as the representative of the same company, establishing offices in Houston, Texas. Late in 1926 he joined the faculty of the Colorado School of Mines and organized the Department of Geophysics, continuing as head of this department to date. Since 1934 he has been president of the Heiland Research Corporation in Denver, Colorado. Dr. Heiland has contributed more than a hundred articles on geophysics to various technical journals and is the author of GEOPHYSICAL EXPLORATION, published in 1940. At present most of his time is devoted to design and production problems for the Army, Navy, and Lend-Lease Departments, and to strategic mineral investigations. He is now serving as chairman of the Geophysics Committee of the American Institute of Mining and Metallurgical Engineers, and is also a member of the American Geophysical Union, the Seismological Society of America, the American Association of Petroleum Geologists, and the Society of Exploration Geophysicists.

FOR SECRETARY-TREASURER

RALPH S. JACKSON

GEORGE E. WAGONER

RALPH S. JACKSON received his B.S. degree in Chemical Engineering from Texas Agricultural and Mechanical College in 1930. He was employed by the Sinclair Refining Company as Test Engineer from 1930 to 1931. He has been associated with the Independent Exploration Company since 1932, serving as Party Chief from 1934 to 1939, Supervisor until 1941 when he was made Vice-President of the company. He is a member of the American Association of Petroleum Geologists, Houston Geological Society and the Society of Exploration Geophysicists.

GEORGE E. WAGONER received a degree of Geological Engineer from the Colorado School of Mines in 1928. He was employed as a Geologist and Geophysicist by John H. Wilson, Consulting Geologist and Geophysicist of Golden, Colorado, from June 1928 to May 1930. He was employed by Humble Oil and Refining Company from 1930 to 1934 as a Torsion Balance Observer, Seismograph Computer, and Seismograph Party Chief. In 1934, he was loaned to The Carter Oil Company as an assistant to the Chief Geophysicist. In 1935, he was transferred to The Carter Oil Company as Supervisor of Geophysical Operations. In 1936, he was transferred to the Standard Oil Company of Louisiana as Chief Geophysicist. In 1937, upon consolidation of Standard Oil of Louisiana with The Carter Oil Company, he returned to Carter as Assistant Chief Geophysicist in charge of Geophysical Exploration. He is a member of the Society of Exploration Geophysicists, The American Association of Petroleum Geologists, and the Tulsa Geological Society.

PACIFIC COAST MEETING OF THE SOCIETY OF EXPLORATION GEOPHYSICISTS

Announcement of the one day technical meeting of the Pacific Coast Section of the S.E.G. was made in the July issue of GEOPHYSICS. As a result of the lifting of O.D.T. restrictions, the meeting was held in close cooperation with the Pacific Section of the A.A.P.G., with a single joint program being printed and distributed outlining the programs for the S.E.G., A.A.P.G. and S.E.P.M.

The morning meeting was opened with an address by Dr. J. J. Jakosky, National Vice-President of S.E.G., followed by a financial report from Mr. Cecil H. Green, National Secretary-Treasurer. The remainder of the morning session consisted of presentation of papers selected from those scheduled to appear in GEOPHYSICS but not yet published at that date.

An informal luncheon in the Spanish Room of the Ambassador Hotel attracted capacity attendance and overflowed into the adjoining French Room.

The afternoon meeting was opened with a presidential address by Mr. Henry C. Cortes. Mr. A. C. Rubel of the Union Oil Company of California addressed the meeting on the subject of "Political and Economic Aspects of a Foreign Exploration Program," and Mr. Howard C. Pyle, Vice-President of the Bank of America and former Deputy Chief of Oil Supply Branch in Europe, spoke on "The Petroleum Supply to the United States Forces in Europe." Remaining papers at the afternoon session, as with the morning meeting, were selected from presently unprinted material subsequently to appear in GEOPHYSICS.

The meeting was well attended and, at its height, attracted a capacity audience of over two hundred, who supplied lively discussion of several papers. Following a brief discussion at the close of the meeting, it was unanimously decided that the Pacific Section of S.E.G. should hold a similar meeting next year with Mr. C. H. Dresbach and Mr. Phil P. Gaby assigned the task of arranging for that meeting.

Success of the meeting this year resulted primarily from the efforts of Mr. O. C. Lester, Chairman of the Pacific Coast Program Committee, Mr. E. H. Vallat, Chairman of the Arrangements Committee for the local meeting, and committee members Mr. H. R. Thornburgh, Mr. C. H. Dresbach, and Mr. Phil P. Gaby. Active sponsorship by three of the national officers (Mr. Henry C. Cortes, Dr. J. J. Jakosky, and Mr. Cecil H. Green) in advance of the meeting and direct participation at the meeting was likewise an important factor. The Pacific Coast membership greatly appreciates the splendid cooperation of authors from other sections in furnishing manuscripts and slides for papers (which necessarily were read by proxy), and also that of the local authors. We are indebted to Dr. L. L. Nettleton, Editor of GEOPHYSICS, for assistance in providing material for the program.

The complete program follows:

WEDNESDAY MORNING

Presiding—J. J. Jakosky, Los Angeles, California
C. H. Dresbach, Western Gulf Oil Co., Los Angeles, California

1. Opening Remarks by Dr. J. J. Jakosky, Vice-President, Society of Exploration Geophysicists.
2. The Attenuation Constant of Earth Materials, II.—W. T. Born, Geophysical Research Corp., Tulsa, Okla. (Read by O. C. Lester)
3. Repeated P-Waves in Seismic Exploration of Water Covered Areas.—Roy L. Lay, The Texas Co., Houston, Texas. (Read by L. B. Snedden)
4. Application of Continuous Profiling for Refraction Shooting.—A. J. Barthelmes, Seismograph Service Corp., Tulsa, Oklahoma. (Read by Joe Waterman)
5. Airplane-Noise Interference with Seismic Prospecting.—J. M. Kendall, Naval Ordnance Laboratory, Washington, D. C. (Read by M. C. Born)
6. Refraction Waves Reflected at a Fault Zone.—W. B. Robinson, Gulf Research & Development Company, Pittsburgh, Pa. (Read by P. F. Clement)

WEDNESDAY AFTERNOON

Presiding—Phil P. Gaby, Geophysical Service Inc., Fresno, Calif.
H. R. Thornburgh, Shell Oil Co., Los Angeles, Calif.

7. Address by the President of the Society of Exploration Geophysicsts.—Henry C. Cortes, Magnolia Petroleum Co., Dallas, Texas.
8. Some Political and Economic Aspects of a Foreign Exploration Program.—A. C. Rubel, Union Oil Co. of California, Los Angeles, California.
9. Recent Developments in Geochemical Prospecting for Petroleum.—Leo Horvitz, Research Laboratories, Houston, Texas. (Read by J. A. Laird)
10. The Petroleum Supply to the United States Forces in Europe.—Howard C Pyle, V.-P. Bank of America, former Lieut.-Col., U. S. Army, Deputy Chief of Oil Supply Branch in Europe.
11. Seismograph Evidence on the Depth of the Salt in Southeast Texas.—H Wayne Hoylman, Gulf Research & Development Company, Pittsburgh, Pa. (Read by C. H. Dresbach)
12. Gravity Results over Kettleman Hills and Lost Hills, California.—Lewis H. Boyd, Brown Geophysical Co., Tallahassee, Florida.

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee has approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

ACTIVE

Paul Davet Balbin
M. B. Widess, K. E. Burg, R. C. Coffin
Lawrence Paul Corbin, Jr.
R. F. Beers, R. Maurice Tripp, C. L. Doss
Fred W. Krause
D. F. Broussard, G. H. Harrington, T. I. Harkins
Loyde Henry Metzner
Louis N. Waterfall, E. H. Vallat, R. W. Clark
Roy Ward Pearce
Adrian E. Mix, Willis R. Dortch, Jr., P. P. Conrad
David Albert Rait, Jr.
T. C. Richards, Richard Davies (Sec. III-D-1 of Constitution)
James Claude Rollins
Joseph A. Sharpe, V. L. Jones, J. M. Rich
David Holcomb Scott
Norman J. Lea, Warren H. Smith, Maurice Sklar
Charles Robert Woodruff
H. L. Thomsen, G. A. Barton, L. F. Schombel
Stanislaw Mieczyslaw Wyrobek
T. C. Richards, Richard Davies (Sec. III-D-1 of Constitution).

ASSOCIATE

Pierre Léon Adelin F. Evrard (Sec. III-D-1 of Constitution).
Theodore Myers Howell
Joseph A. Sharpe, James E. Woodburn, William M. Erdahl
Leon Migaux (Letter, E. G. Leonardon; Sec. III-D-1 of Constitution).
John Randolph Strong, Jr.
Wayne H. Denning, Martin Eichelberger, Jr., Decio Severio Oddone
Robert Phillip Wilkinson
T. C. Richards, Richard Davies (Sec. III-D-1 of Constitution).

STUDENT

Jonathan Ewart Blanchard
John H. Hodgson
Leonard Stanier Collett
John H. Hodgson
Albert Edward Johnson
John H. Hodgson
Walter James MacNeill
John H. Hodgson
Lawrence Whitaker Morley
John H. Hodgson
Melville Edgar Woods
HJohn H. odgson

TRANSFER TO ACTIVE MEMBERSHIP

C. Y. Fu
Millard L. Suggs

RESIGNED

L. A. Burrows
John C. Maher

STATEMENT OF THE OWNERSHIP, MANAGEMENT, CIRCULATION, ETC., REQUIRED BY THE ACTS OF CONGRESS OF AUGUST 24, 1912 AND MARCH 3, 1933

of GEOPHYSICS, published quarterly at Menasha, Wisconsin, for January, 1946

State of Texas }
County of Hamilton } ss.

Before me, a Notary Public in and for the State and county aforesaid, personally appeared E. Stiles, who, having been duly sworn according to law, deposes and says that he is the business manager of GEOPHYSICS, and that the following is, to the best of his knowledge and beliefs a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

1. That the names and addresses of the publisher, editor, managing editor, and business manager are: Publisher, Society of Exploration Geophysicists, Hamilton, Texas; Editor, Dr. L. L. Nettleton, P. O. Box 2038, Pittsburgh, Pa.; Managing Editor, Dr. L. L. Nettleton, P. O. Box 2038, Pittsburgh, Pa.; Business Manager, E. Stiles, Hamilton, Texas.

2. That the owner is: Society of Exploration Geophysicists, Hamilton Texas; Henry C. Cortes, President, P. O. Box 900, Dallas, Texas; J. J. Jakosky, Vice-President, 1063 Gayley Ave., Los Angeles, California; W. M. Rust, Jr., Past-President, P. O. Box 2180, Houston, Texas; Cecil H. Green, Secretary-Treasurer, 1311 Republic Bank Bldg., Dallas, Texas.

3. That the known bondholders, mortgagees, and other security holders owning or holding 1 per cent or more of total amount of bonds, mortgages, or other securities are: None.

4. That the two paragraphs next above, giving the names of the owners, stockholders, and security holders, if any, contain not only the list of stockholders and security holders as they appear upon the books of the company but also, in cases where the stockholder or security holder appears upon the books of the company as trustee or in any other fiduciary relation, the name of the person or corporation for whom such trustee is acting, is given; also that the said two paragraphs contain statements embracing affiant's full knowledge and belief as to the circumstances and conditions under which stockholders and security holders who do not appear upon the books of the company as trustees, hold stock and securities in a capacity other than that of a bona fide owner; and this affiant has no reason to believe that any other person, association, or corporation has any interest direct or indirect in the said stock, bonds, or other securities than as so stated by him.

5. That the average number of copies of each issue of this publication sold or distributed, through the mails or otherwise, to paid subscribers during the twelve months preceding the date shown above is not required.

E. STILES (Signed)

Sworn to and subscribed before me this 8th day of October 1945.

[SEAL] MRS. EDNA CONNER (Signed)

(My commission expires June 1947.)

PERSONAL ITEMS

STEWART C. PALMERSTON, of the United Geophysical Company, is now at Aptdo Aereo 465, Barranquilla, Colombia, S. A.

ROBERT J. URICK has been transferred from the U. S. Navy Radio & Sound Laboratory at San Diego to the Sound Division of Naval Research Laboratory at Washington, D. C.

R. H. DANA, formerly with the United Geophysical Company, has joined the Southern Geophysical Company, Sinclair Bldg., Ft. Worth 2, Texas.

Lt. JULIAN HAWES, U.S.N.R., is now at 2618 South Wayne, Arlington, Va.

ABDUL K. MEHTA, has returned to India, and is now Managing Director of Mehta Brothers Ltd., Box 2449, Calcutta, India.

J. W. HOOVER has been transferred from Lexington, Ky., to New Orleans, where he may be addressed at 420 Darrington, Zone 20.

G. C. HOWARD now holds the position of Assistant Geophysical Supervisor with the Union Producing Company, Box 1407, Shreveport, La.

R. R. THOMPSON has left the Harvard Underwater Sound Laboratory, and is now with the Humble Oil & Refining Company at Houston, Texas.

H. M. HOUGHTON has completed his work for the U. S. Engineers on measurements of the earth shock from the Atomic Bomb, and is now with the Geotechnical Corporation, stationed at Bow Island, Alberta, Canada.

FRANK R. KITTREDGE is now at Room 1205, Hunt Bldg., Tulsa, Oklahoma.

WALTER O. NOVELLY, recently with the Seismograph Service Corporation, has gone with the Republic Exploration Company as Party Chief. He may be addressed at Box 2208, Tulsa, Oklahoma.

D. J. WOLFF is now with the Kerlyn Oil Company at 2020 First National Bank Building, Oklahoma City, Okla.

THEODORE ROZSA has been transferred from Saginaw, Michigan, to Midland, Texas, where he may be reached at Box 1509.

W. GORDON SMITH, formerly of the Venezuelan Oil & Transport Company at Barcelona, has returned to England and may be addressed at 14 Kitchener Terrace, Jarrow, County Durham.

LYNN G. HOWELL has left the Applied Physics Laboratory at Johns Hopkins University, Silver Spring, Md., and is now located at 2632 Prospect St., Houston 4, Texas.

DR. DARRELL S. HUGHES is now teaching in the Department of Physics, University of Texas, at Austin, Texas.

The Rieber Research Laboratories have been moved to 127 E. 73rd St., New York 21, N. Y.

JOHN C. STICK, JR., has finished work with the Division of Physical War Research, Durham, N. C., Duke University, and is now located in South Pasadena, California, at 1701 Bushnell Ave.

W. B. PERRY, of the Kingwood Oil Company, is now in Jackson, Mississippi. His address there is Box 1084.

DONALD R. BROWN, formerly with the Shell Oil Company at Houston, Texas, is leaving for Caracas to take the position of Chief Geophysicist with the Caribbean Petroleum Company there.

R. C. COLE, formerly with the Stanolind Oil and Gas Company is now with the Carr Geophysical Company, 1334 Commerce Bldg., Houston, Texas.

LT. COMDR. MARION H. GILMORE has been released from the naval service and has returned to the U. S. Coast & Geodetic Survey. He will be in Washington during the coming year, at 1750 North Troy St., Apartment 695, Arlington, Va.

GEORGE L. PARKHURST has left the Stanolind Oil and Gas Company and is now Vice-President of the Oronite Chemical Company, Russ Bldg., San Francisco, Calif.

WILLIS P. MARTENS has recently been promoted to the position of Party Chief by the Seismograph Service Corporation. He is now at Box 1590, Tulsa, Oklahoma.

HAROLD J. KIDDER, whose home address is 3615 Hall St., Dallas 4, Texas, has gone to South America for the Socony-Vacuum Oil Company, and may be addressed in their care at Bogotá, Colombia, S. A.

DR. JOSEPH A. SHARPE, Vice-President of C. H. Frost Gravimetric Surveys, Inc., spoke to the Oklahoma City Geological Society on November 21st, and to the Kansas Geological Society on the occasion of its annual dinner meeting on December 18th, on the subject "Necessity for Geologic Participation in the Prosecution of Geophysical Surveys."

C. J. CHAPMAN, a recent addition to the Society rolls, has been promoted to the position of computer on his seismic crew by his company, the Imperial Oil, Limited. His address is Box 87, Wainright, Alta., Canada.

C. H. ACHESON, formerly party chief of gravity meter work in Colombia and later in western and northwestern Canada, has been transferred to Ecuador, to take up duties as Gravity Meter Supervisor for the International Ecuadorian Petroleum Company in Guayaquil, Ecuador.

FRED T. FERGUSON, formerly supervisor with the Brown Geophysical Company, Tallahassee, Florida, is now with the Geological Ddpartment of the Ohio Oil Company, and may be addressed at 701 E. Park Avenue, Tallahassee, Fla.

H. L. RASÉ, JR., has been transferred from the Geophysics Department of the Gulf Research & Development Company Laboratory in Harmarville, Pennsylvania, to Gulf Party No. 8 as geophysicist on that party, now in Mississippi. His current address is Box 604, McComb, Miss.

MAJOR LEONARD F. UHRIG, headquartering again at 3801 Villanova, Houston, Texas.

DONALD M. DAVIS, formerly geologist with the Richfield Oil Corporation at Bakersfield, California, is now Scout for the San Joaquin Valley and Northern Division of the Union Oil Company of California, at 1700 19th St., Bakersfield, Calif.

ALBERT W. MUSGRAVE RT2/C has recently been transferred to the Industrial Command Division 12-I, Naval Repair Base, San Diego 36, Calif.

NOYES D. SMITH, JR., has left 122 North Wakefield, Arlington, Va., and is now with the Shell Exploration and Production Laboratory, at 3705 Bellaire Blvd., Houston 5, Texas.

E. JOE SHIMEK, formerly with the Magnolia Petroleum Company, at Dallas, has moved to Houston and established an independent consulting practice in geophysics. He will headquarter in Houston, where he has located a research laboratory owned and operated jointly with the Brown Geophysical Company, of Houston. He may be addressed at Box 6005, Houston, Texas.

HILMI F. SAGOCI has accepted a position as geophysicist with the Turkish Government, and sailed for Turkey on January 10th. His new address will be in care of Maden Tetkik ve Arama Enstitüsü, Ankara, Turkey.

W. J. HARKEY, Party Chief with the National Geophysical Company, Inc., has returned to the Company after four years' leave for war service, and is at present at Box 852, Big Lake, Texas.

DR. MELVIN C. TERRY, who has been serving at the U. S. Naval Ordnance Laboratory, Washington, D. C., is now back with the Humble Oil and Refining Company at Houston, Texas.

Every mail now brings welcome news of the safe return of some member or members of the Society from war service, at home or abroad, to commercial or scientific geophysical work. Among those recently noted are:

CAPT. L. A. SMITHERMAN, late of Wright Field, Dayton, Ohio, now at Box 67, Athens, Texas.

LT. NAT H. PRADE, U.S.N.R., once again Mr. N. H. Prade, of 201 Abiso Ave., San Antonio 2, Texas.

LT.-COL. HARVEY CASH, JR., back from Washington, D. C., and now with the Geophysical Division of The Texas Company again, at Houston, Texas.

LT. COMDR. JOHN W. FLUDE, recently stationed at Galveston, but now at home at 3039 Locke Lane, Houston, Texas.

LT. PATRICK E. HAGGERTY, U.S.N.R., now located at 6434 Kenmore Road, Dallas 5, Texas.

CAPT. HARRY R. IMLE, recently addressed c/o P.M., San Francisco, now at 1809 Dearborn St., Lawton, Okla.

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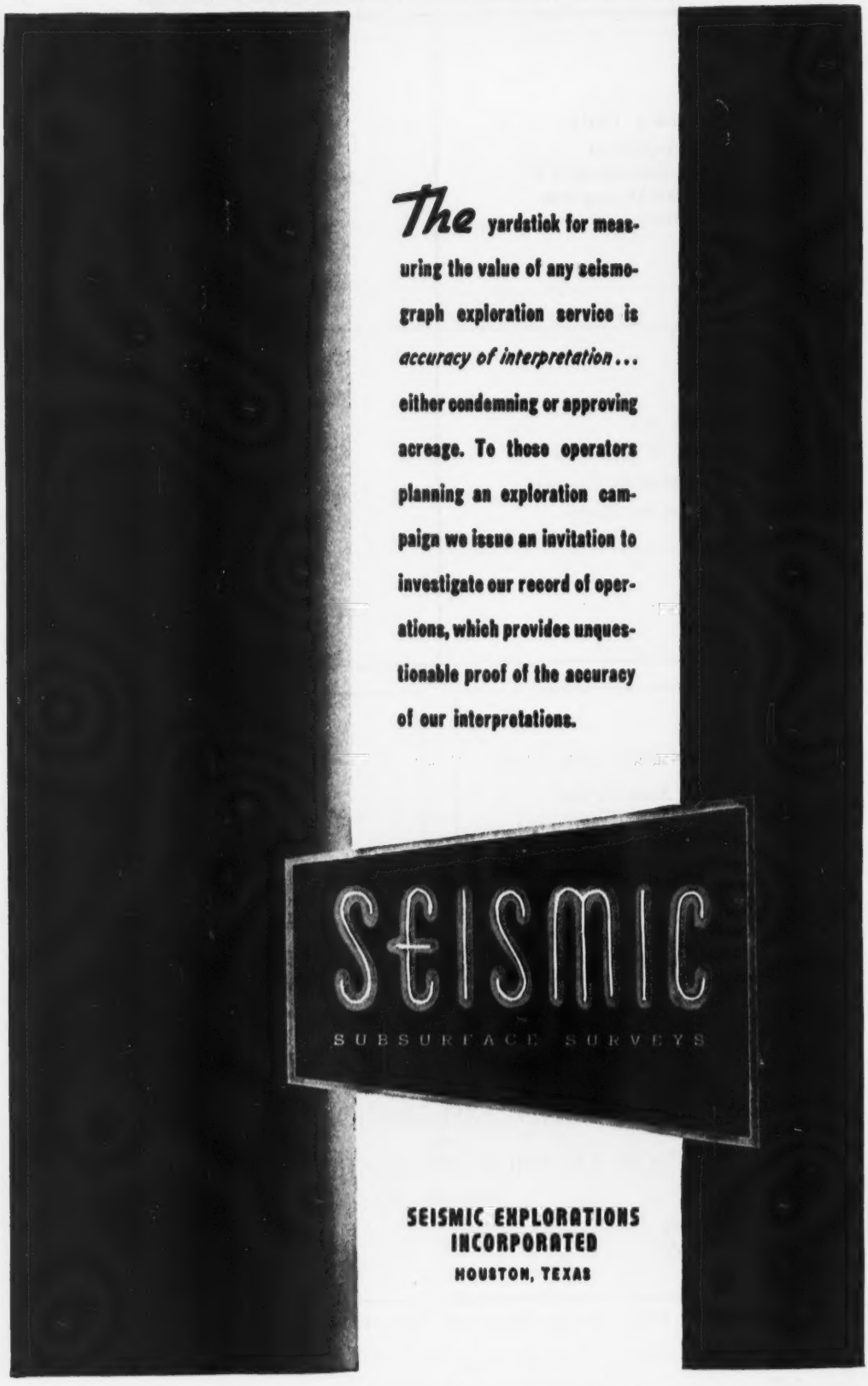
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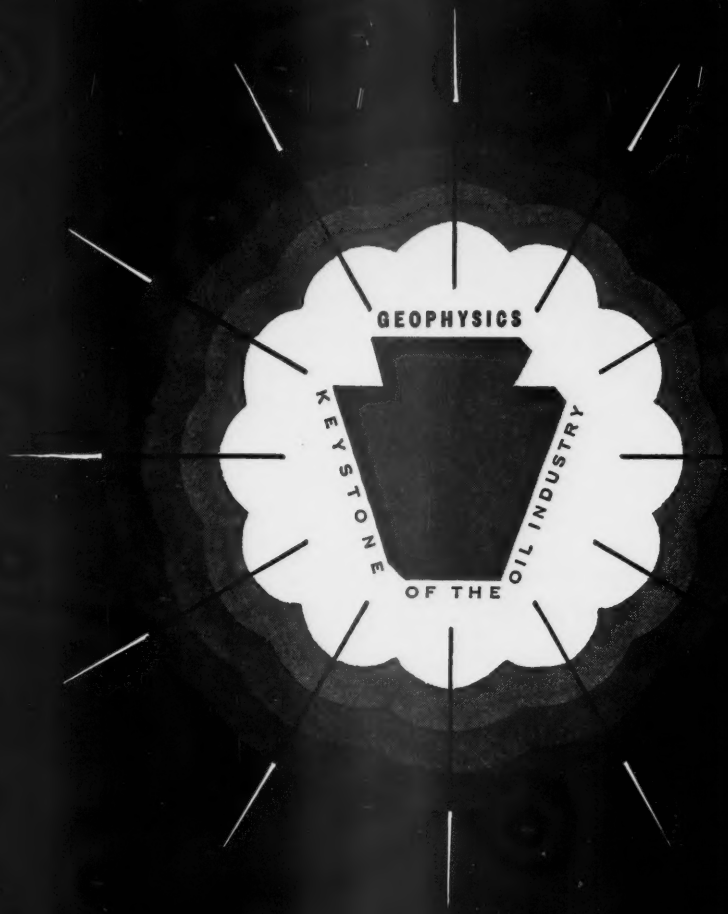

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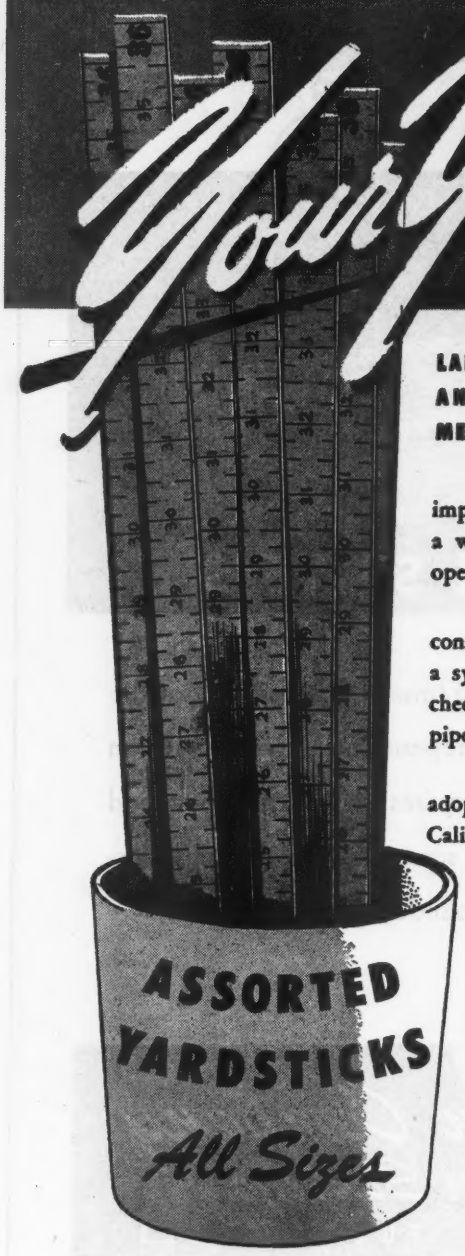

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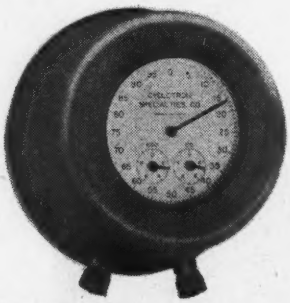

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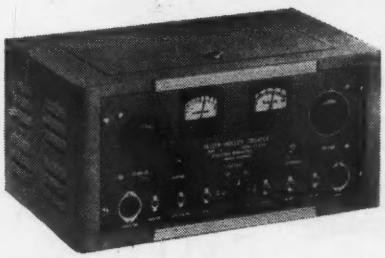

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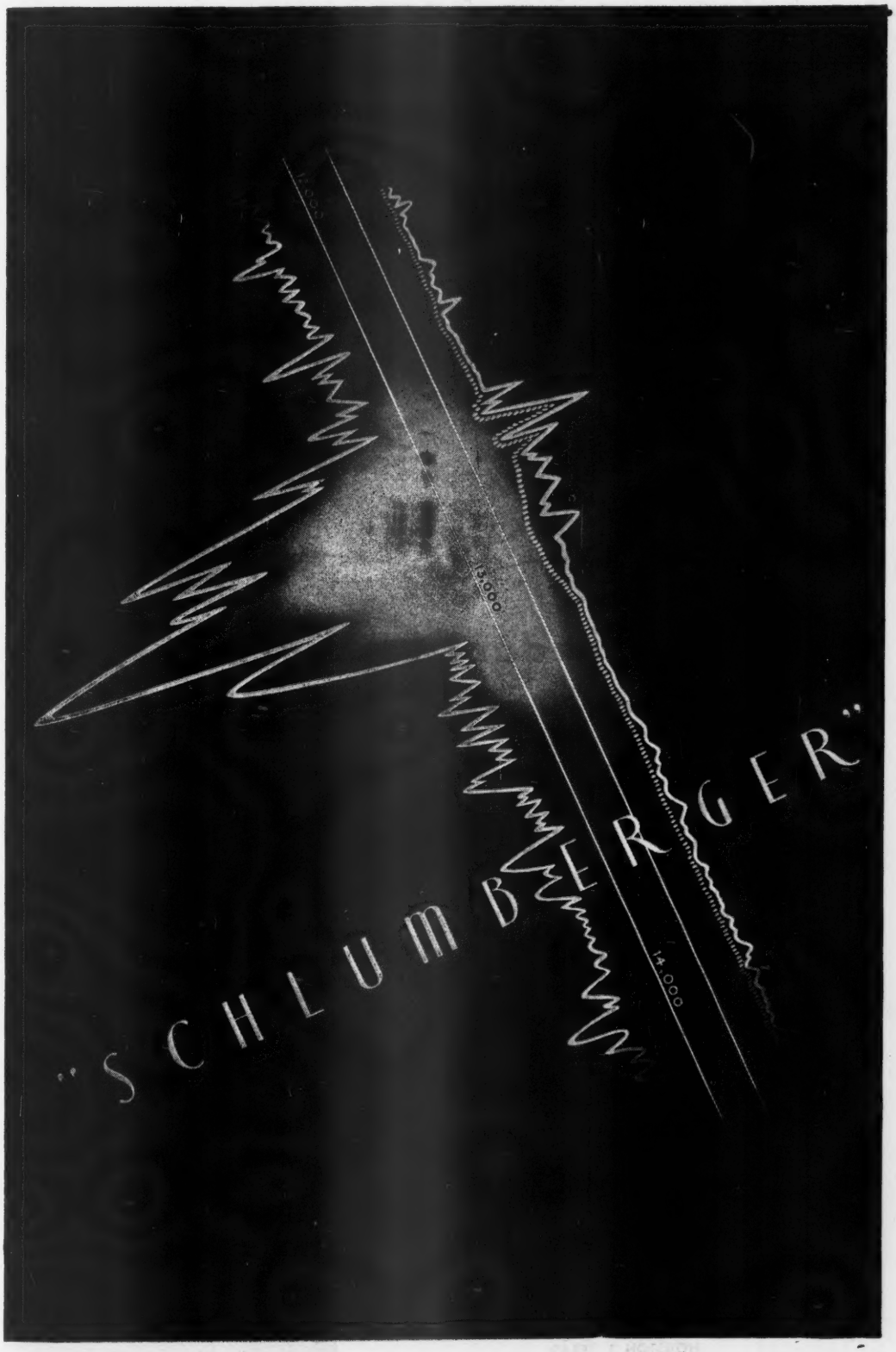
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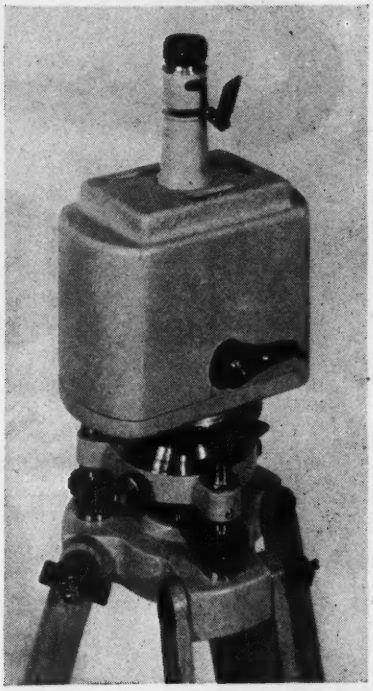

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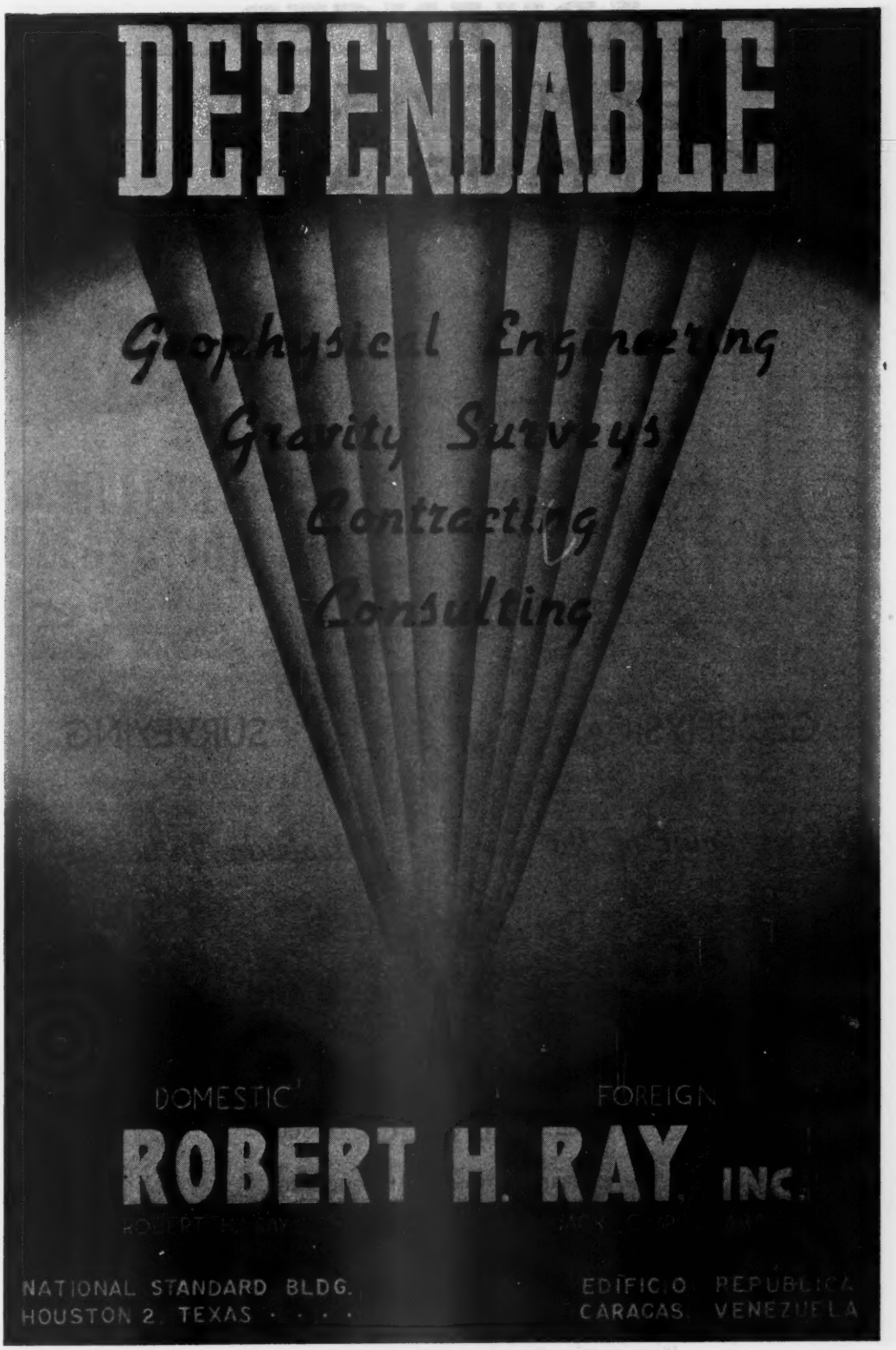
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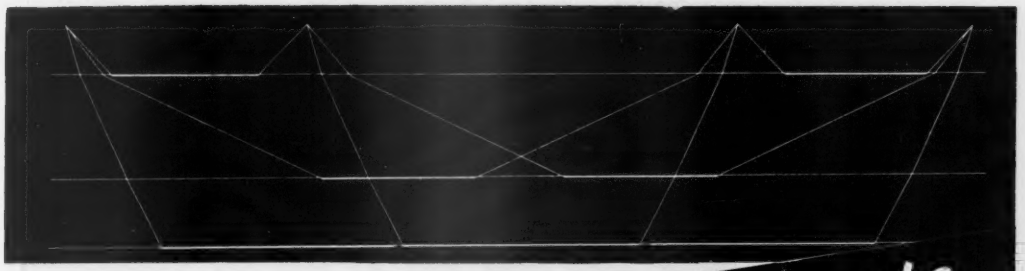

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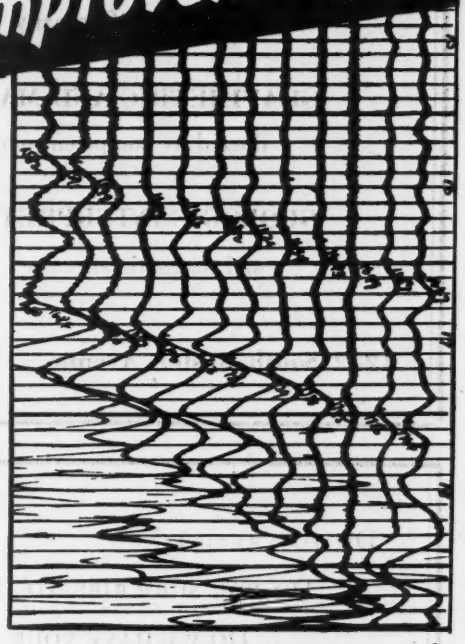

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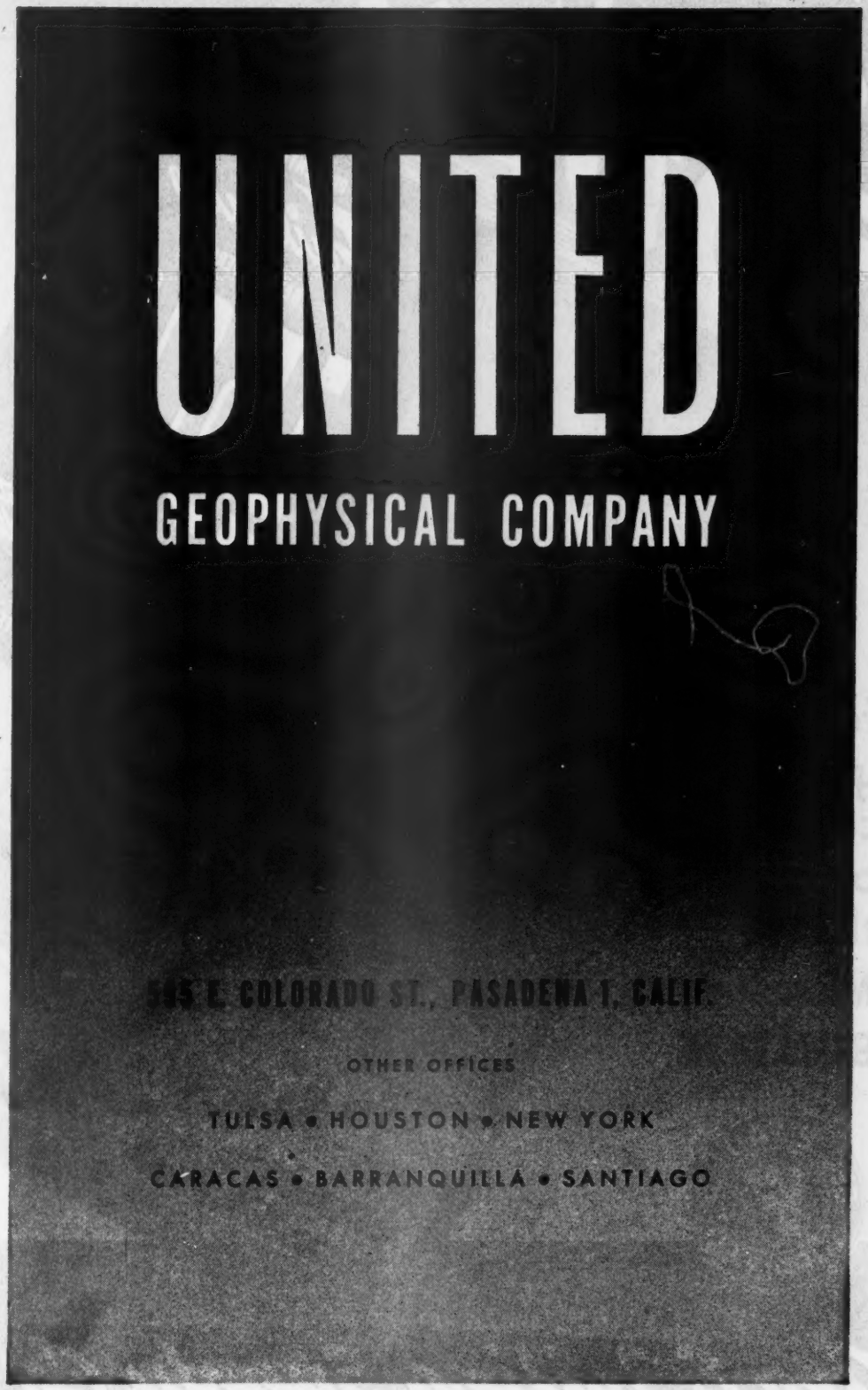
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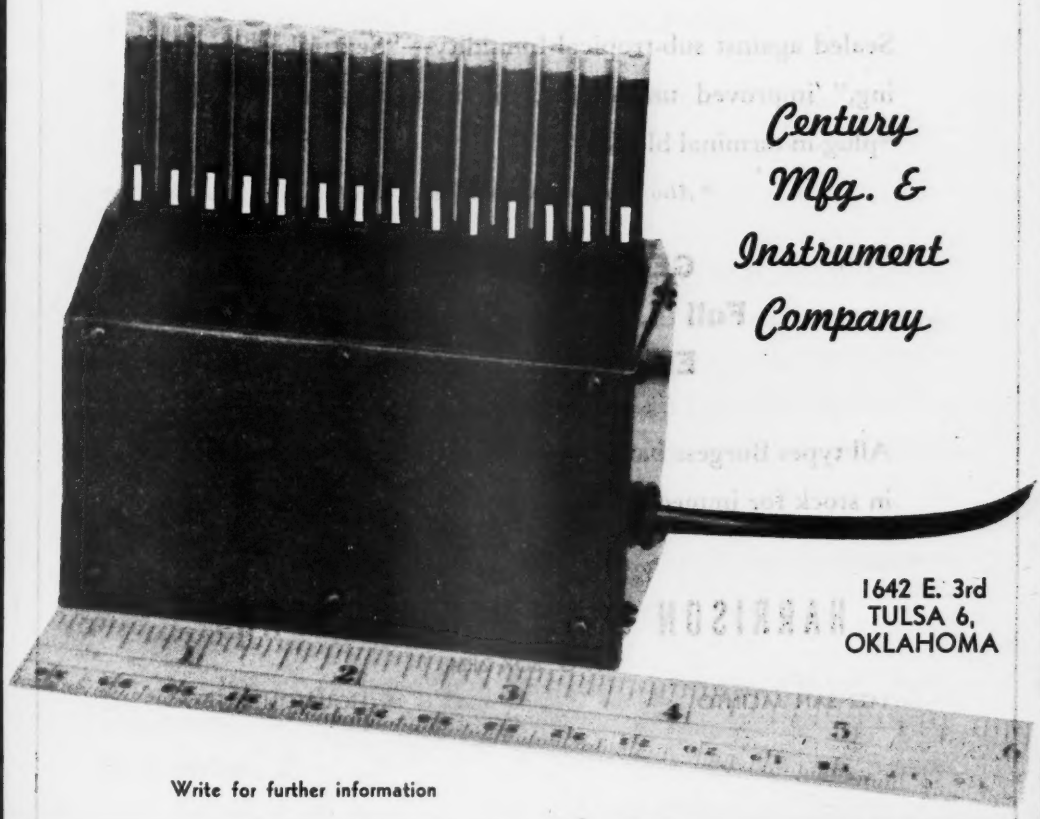

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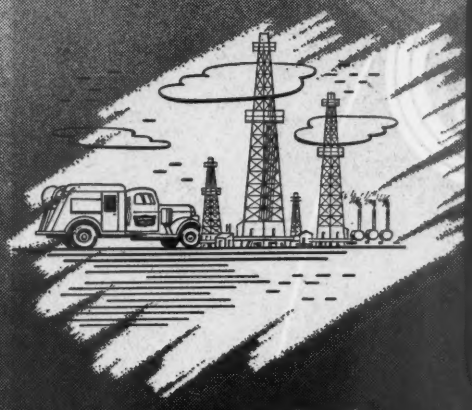

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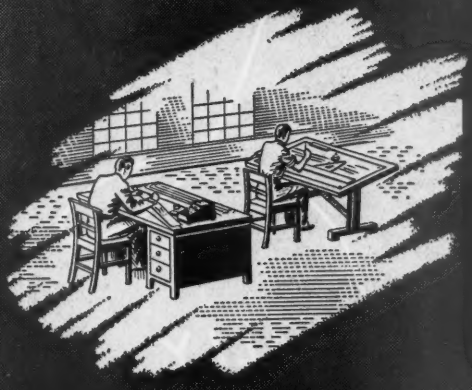

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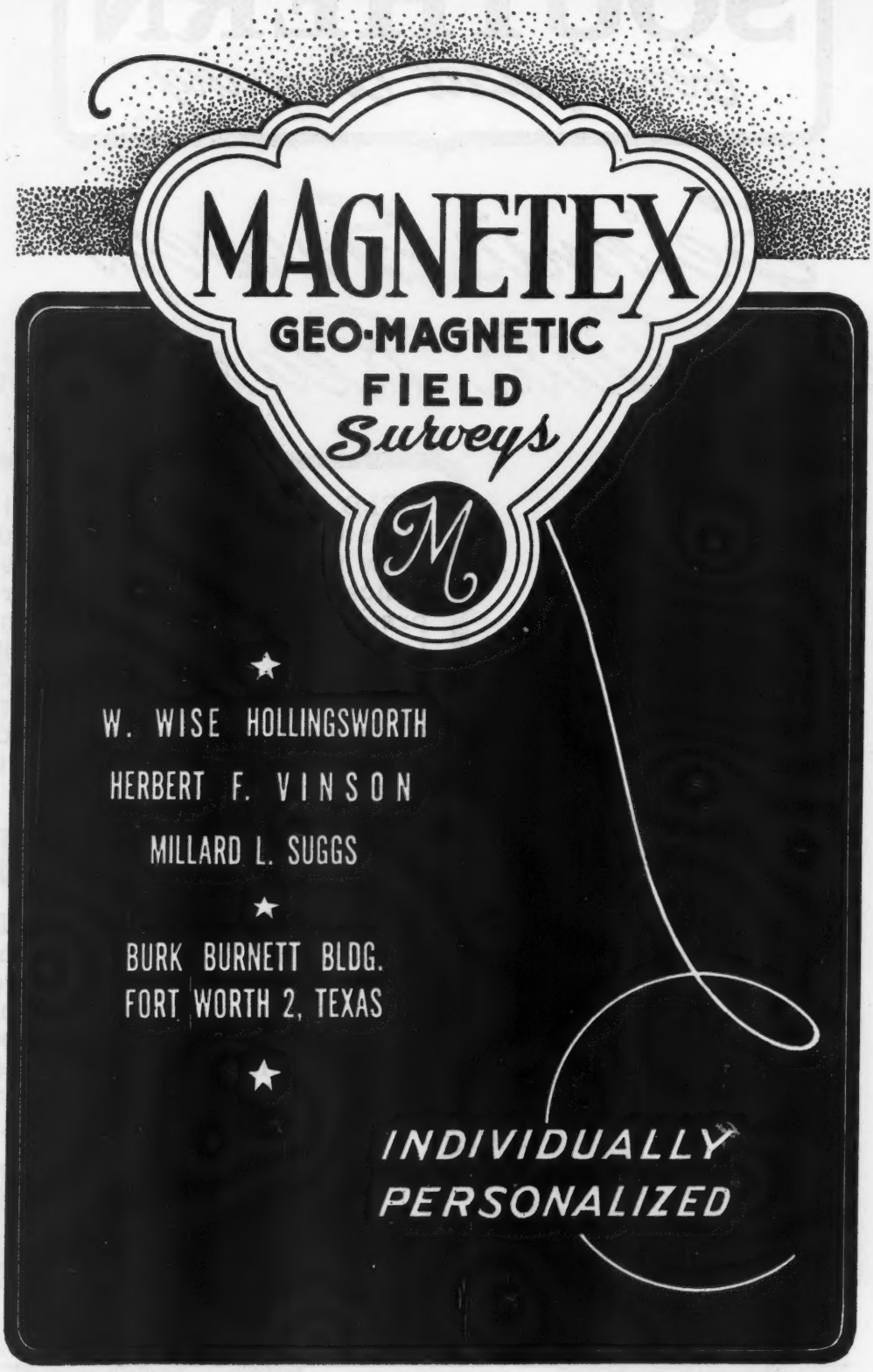
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